DEVELOPMENT OF WELDING TECHNIQUES AND FILLER METALS FOR HIGH STRENGTH ALUMINUM ALLOYS

Second Quarterly Report
Project No. 07-1063

by

N. G. Lenamond
K. K. Speirs
E. B. Norris
D. L. Davidson
A. L. Lowenberg

Reporting Period
1 October 1964 to 31 December 1964

for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama
Attn: PR-EC

Contract No. NAS 8-1529

29 January 1965
(Revised 9 June 1965)

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FOREWORD

This report entitled, "Development of Welding Techniques and Filler Metals for High Strength Aluminum Alloys," was prepared by the Southwest Research Institute under Contract No. NAS 8-1529 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration.

The work was administered under the direction of the Propulsion and Vehicle Engineering Division, Engineering Materials Branch of the George C. Marshall Space Flight Center with Mr. Richard A. Davis acting as Project Manager.

ABSTRACT

During the current reporting period, the bulge test program, organized for the evaluation of the MIG and TIG welding processes and for the determination of the biaxial to uniaxial strength ratio of aluminum alloy weldments, was completed. The results of this series of tests indicate that both the uniaxial and biaxial ultimate strength of TIG 2014-T6/4043 weldments exceed those of MIG 2014-T6/4043 weldments. No significant differences were noted in the average mechanical properties of MIG and TIG 2219-T87/2319 weldments. The uniaxial to biaxial strength ratios measured for all welded panels and for the annealed 2219 base metal panel were less than one (0.84 to 0.89) in contrast to a value of 1.06 measured for 2219-T87 base metal panels.

The membrane stress formula has been used for the calculation of biaxial ultimate strength from hydraulic bulge test results. At the present time, some uncertainty exists as to the suitability of this formula for the determination of the absolute value of biaxial strength. The results of a limited study of the applicability of this formula indicate that further work is necessary to establish an expression relating the stress in a bulge panel to the parameters of the hydraulic bulge test.

The test program for the evaluation of the weldability of X7106-T63 aluminum alloy was initiated during this report period. Tensile tests and hardness surveys of TIG weldments aged for periods of up to eight weeks have been completed.

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I. WORK ACCOMPLISHED DURING LAST MONTHLY REPORTING PERIOD

During the last monthly reporting period, the laboratory tests of the MIG and TIG welding process evaluation were completed.

The weldability study of X7106 was continued. Natural aging characteristics of weldments,as evaluated by tensile and hardness tests, were determined through eight weeks.

II. INTRODUCTION

The current scope of work for this program is divided into two separate phases. One phase of the program is directed toward the evaluation of the Tungsten Inert Gas (TIG) and the Metal Inert Gas (MIG) processes and the determination of the biaxial to uniaxial strength ratio for aluminum alloy weldments. This phase is based on the utilization of hydraulic bulge tests and uniaxial tensile tests of various types of weldments. The second phase of the program consists of a study of the weldability of X7106-T63 aluminum alloy. The objective of this second phase is to establish the mechanical properties and metallurgical characteristics of MIG and TIG weldments of this alloy made with those filler metals most likely to be applicable to production.

The schedule of bulge tests to be carried out for the purpose of evaluation of the MIG and TIG welding processes has been previously established.* This series of bulge tests was initiated during the previous quarter. During the current reporting period the hydraulic bulge tests of all panels included in this program were completed.

In addition to the tests performed for evaluation of the two welding processes, an additional set of tests was performed to establish the biaxial ultimate strength to uniaxial strength ratio for various 2219-T87 weldments. This test series was organized to investigate the influence of residual stresses and geometrical notches on the biaxial strength to uniaxial strength

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* Contract No. NAS 8-1529, Project 07-1063 Fourth Year, First Quarterly Report, Southwest Research Institute, San Antonio, Texas, October 1964.

ratio.

The test program for the evaluation of the weldability of X7106-T63 aluminum alloy was initiated during this reporting period. This program includes a study of the natural aging characteristics of MIG and TIG weldments of this alloy.

III. EXPERIMENTAL PROCEDURE

A. Welding Process Evaluation

The bulge tests utilized in this program were performed in accordance with the procedures previously established.* In the course of each test the bulge height and pressure are monitored simultaneously from the beginning of the test to rupture of the test panel. The test panels used in the evaluation of the MIG and TIG welding processes included single welds, "Tee" welds and cross welds to simulate conditions encountered in production. The welding procedures utilized for panels fabricated and tested in this report period are listed in Table I. All welded panels were radiographed after fabrication to establish the integrity of each weld. The radiographic procedure is described in Table II and the results of these inspections are listed in Table III.

The various combinations of material, filler metal and welding process evaluated are as follows:

Process	Alloy	Filler Metal
TIG	2014-T6	2319
TIG	2014-T6	4043
MIG	2014-T6	4043
TIG	2219-T87	2319
MIG	2219-T87	2319

It should be noted that the MIG 2014-T6/2319 weldments, originally included in the program, have been eliminated. This combination of base metal and filler metal proved to be very crack sensitive, and efforts to produce

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* Contract No. NAS 8-1529, Project 07-1063 Fourth Year, First Quarterly Report, Southwest Research Institute, October 1964.

sound welds with welding procedures comparable with those used for the other combinations were unsuccessful. The excessive crack sensitivity of MIG 2014-T6/2319 weldments has been observed both at Southwest Research Institute and at NASA, Huntsville, Alabama.

B. Investigation of Biaxial to Uniaxial Strength Ratio

In previous tests it has been observed that the biaxial to uniaxial strength ratio for welded panels, as measured by the bulge test, was consistently less than one (0.68 - 0.92) in contrast to the results obtained on base metal panels. As a result, a series of tests was conducted to determine the influence of residual stresses, stress concentration at the weld crown and welding procedure on the biaxial to uniaxial strength ratio.

The influence of residual stresses was investigated by a series of tests performed on annealed panels. The specimens for this series of tests consisted of three TIG 2219-T87/2319 single-weld panels (BP-40, BP-41, BP-42) and three 2219-T87 base metal panels (BMA1, BMA2, BMA3) each 1/8" x 30" x 36". The welded panels were fabricated by welding procedure 64A-2. Each of the six panels was heated to 850°F ±25°F for 1-1/2 hours, furnace cooled to 200°F at a maximum rate of 50°F per hour, then air cooled. During the annealing treatment the panels were clamped between 1/4-inch steel plates to minimize warping.

Two additional panel types were also included in this test series. Three panels (BP-47, BP-48, BP-50) were fabricated with a single V-groove, 5-pass joint, and three panels (BP-44, BP-45, BP-46) were fabricated with a single-pass joint and tested with the weld crowns ground flush. The 5-pass panels were included to investigate the influence of residual stresses introduced by a multiple-pass welding procedure while the second group was tested to determine the influence of stress concentrations at the toe of a weld bead.

Uniaxial tensile test specimens were cut from each panel and tested as previously described. The results of the bulge tests and uniaxial tests on annealed panels were compared with those of the tests on as-fabricated panels performed in the MIG and TIG evaluation series.

In addition to the tests described above, direct measurements of the residual stresses in several weldments were made. For this purpose, resistance strain gages were mounted in appropriate locations on each of the panels after fabrication. One-inch squares, containing each gage, were then cut from the panel and the relaxation strains were measured using conventional procedures and instruments. The residual stresses were calculated from these strain measurements.

The types of weldments, locations of gages and conditions of each test were as follows:

1) Panel 2-SG: TIG 2219-T87/2319 single-weld panel fabricated by procedure 64A-2. Three 120° rosettes (1/32-inch gage length) mounted on center line of the weld. Gages mounted after removal of panel from positioner. Panel replaced in positioner, clamped and strain due to clamping recorded.

2) Panels 3-SG and 5-SG: TIG 2219-T87/2319 single-weld panels fabricated by procedure 64A-2. Three 120° rosettes (1/32-inch gage length)

on center line of weld and two 1/64-inch single gages mounted in heat-affected zone,* one parallel to weld centerline and one perpendicular to the weld centerline. Gages mounted before panel was removed from positioner. The strain arising from release of clamps was recorded.

3) Panels 6-SG and 7-SG: MIG 2219-T87/2319 single-weld panels fabricated by procedure 64A-4. Number of gages and procedure same as for Panels 3-SG and 5-SG.

4) Panel 4-SG: TIG 2219-T87/2319 single-weld panel fabricated by procedure 64A-5 (single V-groove, 5-pass). Three 120° rossettes (1/32-inch gage length) on center line of weld. Gages mounted after panel was removed from positioner. Panel replaced in positioner, clamped and strain due to clamping recorded.

C. Weldability of X7106-T63 Alloy

The weldability of X7106-T63 alloy is being evaluated by means of a series of tensile tests and hardness surveys of specimens of MIG and TIG weldments made with X5180, 5356 and 5556 filler metal alloys. The tests are performed on specimens cut from 0.090-inch sheet weldments after various periods of aging at room temperature. The schedule of tests in this series, along with the current status of the test program, is given in Table IV.

* The term "heat-affected zone" is used in this report to describe the zone of heat-affected base metal, adjacent to the fusion line, revealed by etching.

The weldments employed in this study consist of 12" x 18" panels, fabricated from two 0.090" x 6" x 18" sheets. The welding procedures employed for the panels fabricated during this reporting period are given in Table I (64A-6 - 64A-8). A grooved, water-cooled, copper back-up bar was used in the fabrication of each panel. During each welding operation, helium gas was directed through the groove in the back-up bar to protect the underside of the weld.

The tensile test specimens cut from these panels conform to ASTM Specification E8-57T, and are prepared so that the welded joint is located at the center of the test specimen. The specimens are tested with the weld crown intact.

The specimens used for the hardness determination consist of coupons cut from the welded panels so as to contain a portion of the welded joint. The weld crowns are ground flush with the surface and the surface is polished and etched. With this procedure the weld metal and heat-affected base metal, as revealed by etching, may be distinguished. Rockwell hardness measurements are then made in each of the respective zones. In addition, microhardness surveys of the weld metal and heat-affected base metal of selected specimens were carried out.

IV. RESULTS AND DISCUSSION

A. Welding Process Evaluation

The results of the individual bulge tests and uniaxial tensile tests conducted during this reporting period are given in Table V. A summary of the average mechanical properties of the panels tested in the welding process evaluation program is given in Table VI. In Tables V and VI the biaxial ultimate strength is reported as the membrane stress at the time of failure, calculated from the equation:

$$\sigma = \frac{P \times R}{2t}$$

Where:

σ = membrane stress, psi

P = hydraulic pressure, psi

R = radius of curvature, inches

t = panel thickness, inches

In each calculation, the radius of curvature R is determined from the bulge height, assuming the bulged portion of the panel to be a segment of a sphere at failure. The applicability of the membrane stress formula to the determination of the biaxial ultimate strength is discussed further in Section IV-C and Appendix A.

All uniaxial tensile test specimens were cut from one end of a test panel and each specimen contained a portion of a single weld in the test section. Thus, there is no basic difference in the tensile test specimens cut from the three types of weld configuration (single, tee or cross). As a result, the mechanical properties measured in tests of all tensile specimens cut from the three weld configurations for each type of weldment were considered as a group for the purpose of computing the mean values and standard deviations listed in Table VI and VII.

As may be noted in Table V, the values of biaxial and uniaxial ultimate strength determined from bulge tests and tensile tests exhibited considerable scatter. The degree of scatter is indicated by the standard deviations listed in Table VII.

An examination of selected bulge panels and tensile specimens was conducted to ascertain whether or not the low values of biaxial and uniaxial ultimate strength correlated with any observable feature of particular specimens or panels. In this study, described in Appendix B, certain variations in the size and shape of the weld beads were noted. However, the magnitudes of these variations are considered to be comparable to those which may be expected in production.

It was observed that the uniaxial mechanical properties of the 2014-T6/4043 weldments exhibited a higher degree of scatter than the other types (Table VII). Such a result may be expected, since the strength of weldments made with 4043 filler wire depends upon alloying of the filler metal with the base metal and is thus subject to variation. In addition, 2014 alloy is widely recognized as exhibiting poor weldability, and the probability of low values of ultimate tensile strength for weldments of this alloy is higher than that for 2219 weldments. The results of the examination of the fractured panels and tensile specimens and the factors associated with the 2014-T6 weldments are such that discarding the results of any particular tensile test is not warranted.

The scatter in the values of biaxial ultimate strength is considered reasonable in the light of the current status of the interpretation of the bulge test data. At this state of the development some uncertainty exists in the determination of the biaxial ultimate strength by means of the membrane stress equation (See Section IV-C and Appendix A). Thus at the present time the observed scatter must be considered as inherent in the bulge test.

The average biaxial ultimate strength for each weld type and configuration and the average uniaxial ultimate strength of each weldment type are plotted in Figure 1. In this figure, the standard deviations for the uniaxial tensile data and the range of results of the bulge tests are also indicated. This plot of the results illustrates that the indicated differences in biaxial ultimate strength for the different weld configurations are of the same order as the range of results for one type of configuration. Thus, these data do not show any significant difference in strength between the three weld configurations for any one type of weldment. On the basis of this observation, the results of the three types of weld configuration may be treated as a single group of data for each type of weldment.

The mean values of biaxial ultimate strength and uniaxial tensile strength for each type of weldment (computed from the results of all tests for a given process-filler metal combination) are listed in Table VII and presented graphically in Figure 2. The standard deviations and lower tolerance limits are also included in Table VII and Figure 2. The lower tolerance limit is computed as a 99% limit for a 95% confidence level (Appendix C).

The results of the tests on 2014-T6/4043 weldments indicate that for this material-filler metal combination the TIG process is superior to the MIG process. The TIG weldments exhibit a slightly higher mean uniaxial ultimate strength and a slightly higher mean biaxial ultimate strength than the MIG weldments. The biaxial and uniaxial lower tolerance limits of ultimate strength for the TIG weldments exceed those of the MIG weldments by 6.3 ksi and 2.7 ksi respectively. The TIG 2014-T6/2319 weldments exhibit a uniaxial ultimate strength comparable to that of the TIG 2014-T6/4043 weldments. The biaxial ultimate strength of the TIG 2014-T6/2319 panels is significantly higher than that of both of the MIG and TIG weldments employing 4043 filler metal. Both the biaxial and uniaxial lower tolerance limits indicate that the TIG weldments made with 2319 filler metal are superior to both TIG and MIG weldments made with 4043 filler wire. It should also be noted that the TIG 2014-T6/2319 weldments exhibit the highest biaxial to uniaxial strength ratios of all the weldments tested.

No significant differences were observed in the mean values of biaxial and uniaxial ultimate strengths for the MIG 2219-T87/2319 and TIG 2219-T87/2319 weldments. The uniaxial lower tolerance limits for the two types of weldments are also comparable. The MIG weldments, however, exhibited a lower tolerance limit of biaxial ultimate strength significantly higher (5.0 ksi) than that of the TIG weldments.

The above comparison of the various weldments is based on the values of biaxial ultimate strength computed by means of the membrane stress formula. As a result, the conclusions drawn are subject to the limitations of the applicability of that formula (See Section IV-C and Appendix A).

B. Investigation of Biaxial to Uniaxial Strength Ratio

The results of the measurements of residual stresses in welded panels are given in Table VIII. In general, the residual stresses in both TIG and MIG welds are roughly equal to the uniaxial yield stresses normally found for the weld metal, as would be expected. In most cases the maximum principal stress was considerably larger than the minimum principal stress. In all cases, the maximum principal stresses were tensile stresses, oriented in a direction parallel to the length of the weld. Very often the minimum principal stress was observed to be compressive, probably resulting from the relatively high value of the maximum principal stress. Although the stress profile through the panel is unknown, in one case the stresses on the underside of the panel (as positioned during welding) were found to be about 4,000 psi less than those measured on the top of the panel. The residual stresses in the heat affected base metal were, in general, roughly the same magnitude as in the weld metal and in the same direction.

Clamping stresses were observed to differ widely in value and in direction. Most of the clamping stresses measured were lower in magnitude and in a perpendicular direction to the maximum residual welding stresses. The stresses calculated from the strain arising from reclamping the panels in the welding positioner (Panels 2 S. G and 4 S. G.) were considerably higher than the stresses determined from the strain occurring on release of the positioner clamps (Panels 3 S. G. , 5 S. G. , 6 S. G. and 7 S. G.).

One additional set of measurements was made to determine the magnitude of the residual stresses in base metal plates prior to welding. These measurements were made on a 1/8" x 16" x 16" panel employing a three-gage rosette mounted at the center of the panel. The residual stresses in the panel were found to be less than 2.0 ksi. Stresses of this magnitude are not considered to be significant relative to the residual stresses measured for welded panels.

The measurement of residual stresses and the significance of such measurements are discussed further in Appendix D.

The results of the individual bulge tests and uniaxial tensile tests conducted to investigate the factors influencing the biaxial to uniaxial strength ratio are presented in Table IX. A summary of the average mechanical properties determined in these tests is given in Table X. The average results of tests on the TIG-2219-T87/2319 weldments (bulge test panels BP7, BP8, and BP9) from the welding process evaluation program are included in Table X to serve as a basis of comparison.

It may be noted in Table X that the biaxial to uniaxial strength ratios for all the welded panels (annealed, multipass and crowns removed) were less than one (0.84 to 0.88) and comparable in magnitude to that of the as-welded panel. These results indicate that neither the residual stresses arising from the welding operation nor the stress concentration associated with the weld crowns influences the biaxial to uniaxial strength ratio. The tests on the annealed 2219 base metal panel resulted in a biaxial to uniaxial strength ratio of 0.89 in contrast to a value of 1.06 measured for 2219-T87 panels (see Table VI).

It should also be noted that the mechanical properties of the annealed weldment and annealed base metal panel are comparable and significantly lower than those of the as-welded panels. The biaxial and uniaxial strengths measured for the multipass weldment are comparable to those of the panel welded with a single pass. The panels tested with weld crown removed exhibited a lower strength (both uniaxial and biaxial) than the as-welded panel but were significiantly stronger than either of the annealed panels.

As in the case of the welding process evaluation, the above conclusions are subject to the limitations inherent in the application of the membrane stress formula to the determination of the biaxial ultimate strength from bulge test results (See Section IV-C and Appendix A).

C. Interpretation of Bulge Test Results

The membrane stress formula, as given in Section IV-A, is derived for a thin sheet formed into a spherical section by hydrostatic pressure. Thus this formula is strictly applicable to the bulge test only in those cases which result in a spherical bulge. In the course of the bulge test program, it was observed that all welded panels tested failed at very low bulge heights, giving rise to doubt as to whether or not such bulged sections were near spherical. In order to check this point, measurements of the shape of the bulge section were made on one annealed base metal panel and one as-welded 2219-T87 panel. In addition, the strain in the base metal of a welded panel was measured as a function of bulge pressure.

This study, described in detail in Appendix A, revealed that the bulged section of both panels deviated from a true spherical section. This deviation was more pronounced in the welded panel (at a low bulge height) than in the case of the base metal panel.

The stresses in the welded panel as determined from the strain measurements, the membrane formula and Timoshenko's formula for a uniformly loaded, circular, flat plate (see Appendix A) were compared. This comparison indicated that, in this case, the flat plate formula gives a better estimate of the stress than does the membrane formula. The observation of this limited study points out that considerable further investigation is necessary for the proper interpretation of bulge test data. Such investigation will require instrumented bulge tests to provide the information necessary to establish the relationship between biaxial ultimate strength and the parameters involved in the bulge test.

At the present stage of development some uncertainty exists as to the applicability of the membrane stress formula to the hydraulic bulge test. However, only very limited data exists as to the suitability of any other formula for this application. It is felt that the use of any of the available formulae is satisfactory for comparative purposes, even though these formulae may not give the correct absolute value of biaxial strength. As a result, the data from the current bulge test series have been analyzed on the basis of the membrane stress formula. It must be emphasized that the conclusions drawn from the analysis are subject to the applicability of the membrane formula. In the event that further investigation provides a stress formula more suitable to the bulge test, the data from this program should be re-evaluated.

D. Weldability of X7106 Alloy

The results of the individual uniaxial tensile tests conducted to establish the mechanical properties of X7106 base material are presented in Table XI. The average properties for each of the thicknesses tested are summarized in Table XII and plotted in Figure 3. As may be noted in Table XII and Figure 3, the 0.187 inch material exhibited the highest strength (longitudinal and transverse) of the four thicknesses, while the lowest values of ultimate strength were recorded for the 0.090 inch material. Three thicknesses (0.181 inch, 0.500 inch and 1.00 inch) exhibited higher properties in the longitudinal direction than in the transverse direction. The reverse is true in the case of the 0.090 inch material. The range of differences in transverse and longitudinal ultimate strengths for specific thicknesses was from 0.6 to 2.6 ksi. A general increase in elongation at fracture with increasing thickness was observed. Average values of elongation of 11.5 percent for the 0.090 inch material to 14.4 percent for the 1.00 inch material were noted.

The microstructure of specimens of each of the four thicknesses was examined. The typical structures observed in longitudinal sections of the 0.090 inch material and the 1.00 inch material are shown in Figures 4 and 5. The 0.090 inch and 0.187 inch material exhibited similar structures and the structures of the 0.500 inch and the 1.00 inch material were comparable. Pronounced elongation of the grains in the rolling direction was evident in all four thicknesses of material. The grain boundries of the thicker plates, however, were not as clearly defined as those of the thinner plates. In the 0.090 inch and the 0.187 inch material the appearance of the grain boundries at high magnification suggests that the grains are outlined by an intermetallic precipitate, Figure 4. No similar indications were noted in the structure of the thicker materials. Large, dark-etching constituents were present throughout the structure of all specimens examined.

The program of tests to establish the natural aging characteristics of X7106 weldments was initiated during this report period. Four TIG weldments have been prepared with three different filler metals as follows:

Panel A	X5180 (4% Mg, 2% Zn)
Panel B	X5180
Panel C	5356 (5% Mg)
Panel D	5556 (5.25% Mg)

On the basis of visual observation of the welding process and finished welds, X7106 appears readily weldable with the above filler metals.

Tensile tests and hardness surveys of specimens of each of the three types of TIG X7106 weldments, aged for periods of one day to eight weeks, have been carried out. The results of the individual tensile tests are listed in Table XIII. The results obtained for each panel are summarized in

Table XIV and plotted in Figures 6 through 9. The observed increases in ultimate strength of the weldments, tested to date, ranged from 5.9 to 8.1 ksi. The corresponding increases in yield strength ranged from 5.5 to 5.9 ksi. The slope of the ultimate strength versus time curve is very near zero at an aging time of eight weeks for each of the types of weldment, indicating that the maximum value of ultimate strength has been reached. The results indicate a further increase in yield strength for aging periods in excess of eight weeks.

Hardness surveys of each type of weldment were conducted on the same schedule as the tensile tests. The complete results of the surveys of the TIG X7106/X5180 weldments, typical of the three types, are shown in Figure 10. The size and location of the weld metal and heat affected zone are indicated in the figure. A general increase in hardness of the weld metal and heat-affected base metal with aging time was observed. At each aging time the heat-affected base metal exhibited a hardness intermediate to that of the weld metal and base metal. After an aging time of eight weeks the hardness of the heat-affected base metal is still lower than that of the base metal.

The increase in hardness for the weld metal and heat-affected base metal with time is compared to the ultimate strength and yield strength of the weldment in Figure 11. This comparison indicates that the change in yield strength and the change in hardness of the heat-affected base metal are closely related. The hardness values for the heat-affected base metal shown in Figure 11 are averages of hardness measurements taken at points 0.1 inch outside of the fusion lines.

The results of the hardness surveys for the three types of weldments after aging times of one day and eight weeks are given in Figure 12. The weldments made with X5180 filler metal exhibited a higher hardness than the other two types after aging one day. The hardness values for the three types of weldment after an aging period of eight weeks are comparable.

In the course of the tensile tests conducted on the X7106 weldments it was observed that the failures occurred predominantly at two locations; within the heat affected zone and at the fusion lines. Examples of failures at these two locations are shown in Figures 13 and 14. The location of the fracture in each individual tensile specimen is indicated in Table XIII and the percentage of failures occurring in the heat-affected base metal is indicated in Table XIV. Sixty-six percent of all tensile specimens tested failed in the heat-affected zone. It should be noted that X7106 is the only alloy investigated in this program for which the strength of the weld deposit was not the limiting factor.

Measurements of the location of the failures in specimens tested after aging periods of one day and one week were made. In these specimens all failures were located in a region between 0.08 inch and 0.32 inch from the fusion line. Cracks were frequently observed at the toes of the welds in specimens which failed in the heat-affected base metal. These cracks were found to extend along the fusion line.

The fractured edge of a heat-affected base metal failure is shown in

Figure 15. The elongated grains are deformed near the fracture surface. At the higher magnification (500X, Figure 15b), the failure appears to be a mixture of transgranular and intergranular fracture.

The toes of the weld crown of one tensile specimen are shown in Figure 16 and are arbitrarily designated "A" and "B". The cast structure of the weld deposit and elongated grains of the heat-affected base metal are clearly distinguished. The arrow points to the toe region of the weld crown where a crack has occurred during tensile testing. This crack is located along the line where the toe of the weld crown overlaps the heat-affected base metal. The crack at Toe "B" is smaller than that at Toe "A".

The intermetallic constituents in Toe "B" are clearly resolved at 500X. The concentration of these constituents in the vicinity of the boundry between the toe and the heat-affected zone is markedly higher than at other locations within the weld metal. This region of high concentration of intermetallic particles is the location where cracks are consistently initiated in tensile test specimens.

Microhardness surveys were conducted on three specimens to establish the variation in hardness across the heat-affected zone. The specimens used for these surveys were as follows:

1) X7106/X5180 (Panel B) aged 2 weeks

2) X7106/5356 (Panel C) aged 4 weeks

3) X7106/X5180 (Panel B) aged 8 weeks

The results of these surveys are presented in Figure 17. Each of the three specimens exhibited a soft region near the outer edge of the heat affected zone (identified by "S" in Figure 17).

The points of low hardness were all located from 0.105 inch to 0.135 inch from the fusion line. Such a region is within the range of the locations of fractures determined for specimens which failed in the heat-affected base metal. This observation suggests that the soft regions are the points of initiation of fracture when failure occurs in the heat-affected zone.

This occurrence of a soft area in the heat-affected zone may be expected on the basis of the time-temperature aging effect of the heat of welding. There is a zone at the lower temperature end of the heat-affected band which reaches a temperature below the solution temperature at which overaging occurs.

A limited investigation of the microstructure of the X7106/X5180 specimen (aged 2 weeks) in the vicinity of the soft region was carried out. The microhardness indentation corresponding to the low hardness point (S) and the two adjacent indentations are shown in Figure 18, together with the microstructure associated with two of the indentations. The microstructures observed (Figure 18 b and c) are characteristic of heat-affected base metal in X7106 weldments. There is some indication of a larger quantity of a finely dispersed, light colored precipitate in the region of lower hardness (circles in Figure 18c) than in the harder region. The size of these precipitates approaches the limit of resolution of optical microscopy. Further investigation of the structure in these regions would require the utilization of electron microscopy.

V. ANTICIPATED WORK

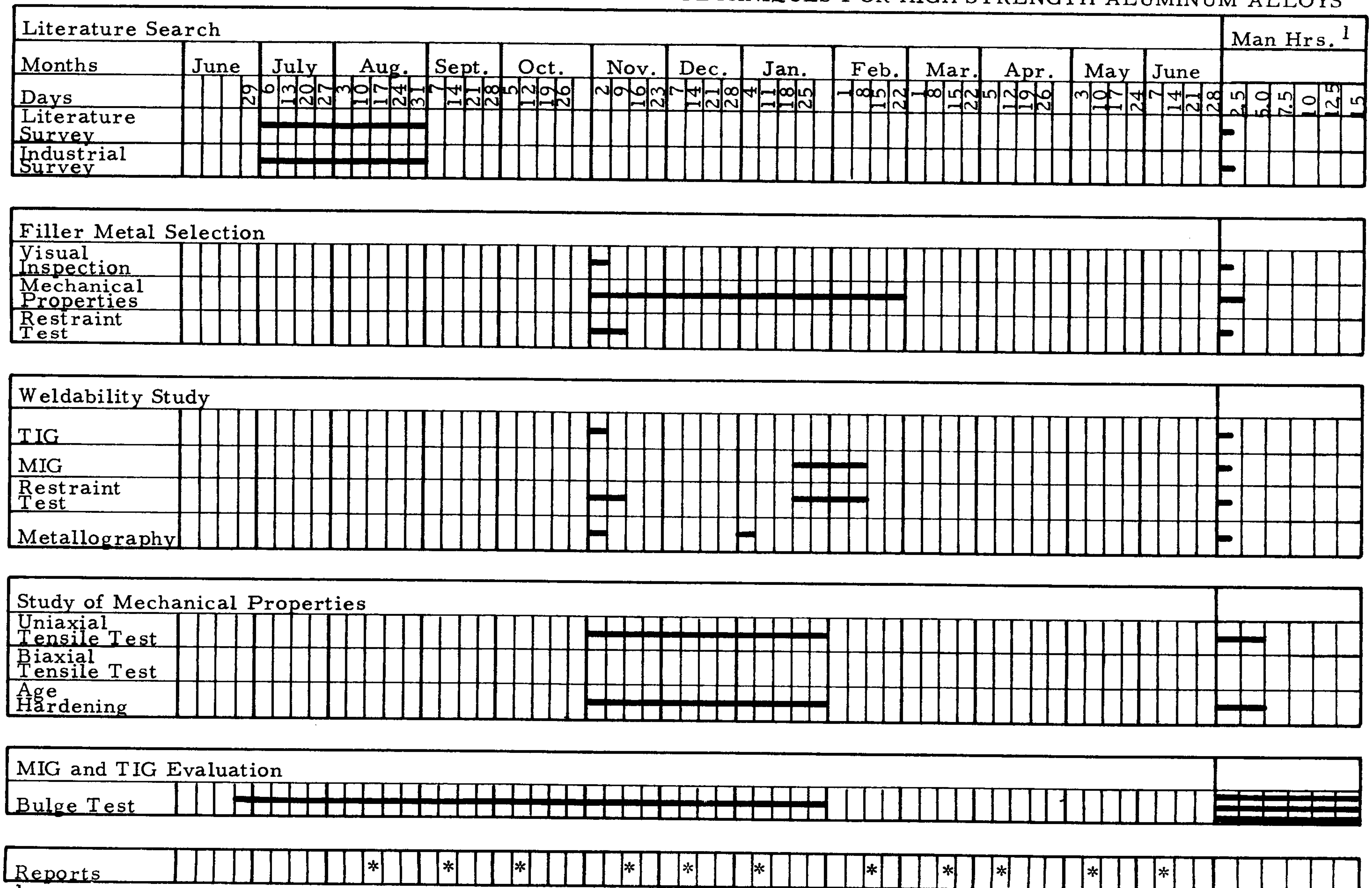
I. Study MIG welding of .090 inch X7106 material.

II. Study natural aging characteristics of X7106 MIG weldments.

III. Study crack susceptibility of X7106 weldments.

VI. PROGRAM PLANNING CHART NO. 6

OVER-ALL OBJECTIVE: INVESTIGATION OF WELDING TECHNIQUES FOR HIGH STRENGTH ALUMINUM ALLOYS



1 Man Hours Required (x 100)

TABLES

TABLE I

WELDING PROCEDURES

Welding Procedure	Alloy/Joint Design	Material Thickness (Inches)	Welding Process	Filler Metal/ Size (Inches)	No. of Passes	Electrode Composition/Size (Inches)	Current (Amps)	Voltage (Volts)	Inert Gas/ Flow (cfh)	Travel Speed (ipm)	Filler Metal Feed (ipm)
64A-1	2014-T6/ Sq. Butt	1/8	TIG	2319/ 3/64	1	Tungsten 2% Thoria/ 1/8	180 DCSP	10.5	He/35	15	35
64A-2	2219-T87/ Sq. Butt	1/8	TIG	2319/ 3/64	1	Tungsten 2% Thoria/ 1/8	180 DCSP	10.5	He/35	15	37
64A-3	2014-T6/ Sq. Butt	1/8	MIG	4043/ 3/64	1	---	200 DCRP	33.5	A/20 He/40	50	--
64A-4	2219-T87/ Sq. Butt	1/8	MIG	2319/ 3/64	1	---	200 DCRP	33.5	A/20 He/40	50	--
64A-5	2219-T87/ Single "V" 90° Included Angle with 1/32-Inch Land	1/8	TIG	2319/ 3/64	5	Tungsten 2% Thoria/ 1/8	180 DCSP	11	He/35	17.5-40	45-68
				Individual Passes							
					1	"	"	"	"	17.5	68
					2	"	"	"	"	40	45
					3	"	"	"	"	40	45
					4	"	"	"	"	40	45
					5	"	"	"	"	40	45

TABLE I (Continued)

WELDING PROCEDURES

Welding Procedure	Alloy/Joint Design	Material Thickness (Inches)	Welding Process	Filler Metal/ Size (Inches)	No. of Passes	Electrode Composition/Size (Inches)	Current (Amps)	Voltage (Volts)	Inert Gas/ Flow (cfh)	Travel Speed (ipm)	Filler Metal Feed (ipm)
64A-6	X7106-T63/ Sq. Butt	.090	TIG	X5180/ 3/64	1	Tungsten 2% Thoria/ 3/32	175 DCSP	11	He/35	22	64
64A-7	X7106-T63/ Sq. Butt	.090	TIG	5356/ 3/64	1	Tungsten 2% Thoria/ 3/32	175 DCSP	11	He/35	22	64
64A-8	X7106-T63/ Sq. Butt	.090	TIG	5556/ 3/64	1	Tungsten 2% Thoria/ 3/32	175 DCSP	11	He/35	22	142
64A-16	2014-T6/ Sq. Butt	1/8	TIG	4043/ 3/64	1	Tungsten 2% Thoria/ 1/8	200 DCSP	11	He/35	15	64

TABLE II

X-RAY PROCEDURE FOR 1/8 INCH ALUMINUM PLATES

Source - Baltospot 150

Strength - 105 KV, 3 ma

Source to Film Distance - 75 Inches

Penetrameter - .25 inch ASME, 1/8 inch shim stock

Film - Kodak Type M (90 mm strip pack)

Exposure Time - 13 minutes

Density - 2

Developing solution - Kodak X-ray developer and replenisher

Developing Time - 5 minutes at 68°F

Fixing Solution - Kodak X-ray fixer

Fixing Time - 10 minutes at 68°F

TABLE III

RADIOGRAPHIC RESULTS OF WELDED PANELS FOR THE WELDING PROCESS EVALUATION

Panel No.	Porosity	Lack of Penetration Length (In.)	Cracking Length (In.)	Misc.	Accepted/ Rejected
1					Accepted
2					Accepted
3					Accepted
4	Slight				Accepted
5	Slight	1/2 inch at start			Accepted
6					Accepted
7					Accepted
8					Accepted
9					Accepted
10					Accepted
12					Accepted
14	Slight				Accepted
15					Accepted
16	Gross				Rejected
17	Slight				Accepted
18					Accepted
19	Slight				Accepted
23	Slight	1/32 inch at start			Accepted
24	1 Spot			Hole	Rejected
25	Slight			Hole	Rejected
26					Accepted
27					Accepted
28	Slight				Accepted
29	Slight				Accepted
30	Slight				Accepted
31	Slight				Accepted
33	Slight				Accepted
35	Slight				Accepted
36	Slight				Accepted
37	Slight		1/4 inch in crater		Accepted
40					Accepted
41	Slight				Accepted
42					Accepted
43			1/2 inch		Rejected
44					Accepted
45					Accepted

TABLE III (continued)

RADIOGRAPHIC RESULTS OF WELDED PANELS FOR THE WELDING PROCESS EVALUATION

Panel No.	Porosity	Lack of Penetration Length (In.)	Cracking Length (In.)	Misc.	Accepted/ Rejected
46		1 inch at start			Accepted
47		1/2 inch at start			Accepted
48		1/2 inch at finish	1/2 inch at start		Accepted
49			1/2 inch		Rejected
50			1 inch at finish		Accepted
51					Accepted
52					Accepted
53					Accepted
54					Accepted
55					Accepted
56					Accepted
57				Tungsten	Accepted
58					Accepted
59				Tungsten	Accepted
60					Accepted
63					Accepted
64					Accepted
65					Accepted
68				Tungsten	Accepted
69					Accepted
70					Accepted
71				Tungsten	Accepted
72					Accepted

TABLE IV

TEST SCHEDULE FOR STUDY OF NATURAL AGING CHARACTERISTICS OF X7106-T63 WELDMENTS

Aging Time	TIG Filler Metal				MIG Filler Metal		
	X5180 Panel A	X5180 Panel B	5356 Panel C	5556 Panel D	X5180 Panel E	5356 Panel F	5556 Panel G
1 day	X	X	X	O	O	--	--
1 week	X	X	X	O	O	--	--
2 weeks	X	X	X	O	O	--	--
4 weeks	X	X	X	O	O	O	O
8 weeks	X	X	X	O	O	--	--
12 weeks	O	--	O	O	O	--	--
16 weeks	O	--	--	--	--	--	--
24 weeks	O	O	O	O	O	O	O

X - Completed tests
O - Scheduled tests

TABLE V

RESULTS FROM INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS FOR THE MIG AND TIG EVALUATION

Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In.)	Max. Press. (psi)	Biaxial Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% Offset(ksi)	Elong.% in 2 In.	Uniaxial Ult	Comments	Comments	Comments
	TIG 2014-T6/ 4043									50.8	41.0	1.8				
										54.3	39.9	1.8				
										47.4	39.1	2.0				
										46.8	38.6	2.0				
BP-54		64A-16	11-24-64	OK	12-3-64	1.58	186	31.9	12-4-64	47.2	37.5	1.6				
										51.6	42.7	2.3				
										43.2	36.2	1.4				
										45.9	38.2	1.6				
										47.5	37.3	1.6				
BP-56	"	64A-16	11-11-64	OK	11-25-64	1.40	195	38.4	11-25-64	51.9	38.1	1.6				
Average						1.49	191	35.2		47.8	38.8	1.8	.74			

TABLE V (continued)

RESULTS FROM INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS FOR THE MIG AND TIG EVALUATION

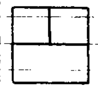
Panel Identification Number	Panel Identification Description	Welding Procedure	Date Welded	Radiograph Results	Bulge Data: Date Tested	Bulge Data: Bulge Ht. (In.)	Bulge Data: Max. Press. (psi)	Bulge Data: Biaxial Ult. (ksi)	Uniaxial Tensile Data: Date Tested	Uniaxial Tensile Data: U.S. (ksi)	Uniaxial Tensile Data: Y.S. 0.2% Offset(ksi)	Uniaxial Tensile Data: Elong.% in 2 In.	Biaxial Ult. / Uniaxial Ult.	Comments	Comments	Comments
	TIG									49.6	39.4	2.0				
	2014-T6/									47.8	38.4	2.3				
	4043									51.1	41.3	2.3				
										53.1	39.6	2.4				
BP-57		64A-16	11-11-64	Small W	12-3-64	1.43	180	34.6	12-4-64	53.9	39.1	3.0		Failed in Weld No. 2		
			11-24-64	Inclusion												
										54.0	40.4	2.5				
										51.6	38.6	2.6				
										53.1	37.3	2.8				
										43.3	38.1	2.2				
BP-58	"	64A-16	11-11-64	OK	12-3-64	1.46	188	35.4	12-4-64	46.9	39.0	1.9		Failed in Weld No. 2		
			11-24-64	OK												
										46.5	39.9	2.1				
										49.4	38.1	2.3				
										57.2	41.5	2.4				
										55.9	41.3	3.0				
BP-59	"	64A-16	11-11-64	Small W	12-3-64	1.46	184	34.6	12-4-64	57.4	40.1	2.1		Failed in Weld No. 2		
			11-23-64	Inclusion												
Average						1.45	184	34.9		51.1	39.5	2.3	.68			

TABLE V (continued)

RESULTS FROM INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS FOR THE MIG AND TIG EVALUATION

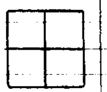
Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In.)	Max. Press. (psi)	Biaxial Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% Offset(ksi)	Elong.% in 2 In.	Uniaxial Ult.	Comments	Comments	Comments
	TIG									47.0	39.7	1.5				
	2014-T6/									41.1	40.7	1.0				
	4043									43.6	42.9	1.5				
										41.7	-	1.0				
BP-51		64A-16	11-11-64	OK	12-3-64	1.41	180	35.1	12-4-64	42.8	39.2	1.7		Failed in Weld No. 2		
			11-24-64	OK												
										47.9	41.4	1.8				
										46.5	41.5	1.4				
										45.4	40.2	1.5				
										43.7	39.0	1.1				
BP-52	"	64A-16	11-12-64	OK	12-3-64	1.41	186	36.3	12-4-64	46.7	41.0	1.6		Failed in Weld No. 1		
			11-24-64													
										42.0	38.2	1.6				
										41.1	40.9	1.5				
										40.0	39.1	1.5				
										42.3	39.8	1.3				
BP-53	"	64A-16	11-12-64	OK	12-3-64	1.43	177	34.1	12-4-64	42.1	39.5	1.9		Failed in Weld No. 2		
			11-24-64													
Average						1.42	181	35.2		43.4	40.2	1.5	.81			

TABLE V (continued)

RESULTS FROM INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS FOR THE MIG AND TIG EVALUATION

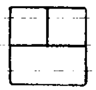
Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In.)	Max. Press. (psi)	Biaxial Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% Offset(ksi)	Elong.% in 2 In.	Uniaxial Ult.	Comments	Comments	Comments
	MIG									43.7	28.6	3.2				
	2219-T87/									43.4	28.7	3.0				
	2319									41.9	28.9	3.4				
										43.5	28.8	2.9				
BP-68		64A-4	12-2-64	Small W	12-17-64	1.51	210	38.6	12-18-64	43.7	28.2	3.1		Failed in Weld No. 2		
			12-9-64	Inclusion												
										42.1	27.7	3.3				
										43.6	29.5	3.6				
										42.0	27.7	3.4				
										41.6	28.8	2.2				
BP-69	"	64A-4	12-2-64	Slight	12-17-64	1.35	181	37.0	12-18-64	41.1	29.7	3.3		Failed in Weld No. 1		
			12-7-64	Porosity												
										41.3	26.2	3.3				
BP-71	"	64A-4	12-7-64	OK	12-17-64	1.42	188	36.4	12-18-64	40.7	31.8	3.2		Failed in Weld No. 2		
			12-7-64													
Average						1.43	193	37.3		42.1	29.0	3.2	.88			

TABLE V (continued)

RESULTS FROM INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS FOR THE MIG AND TIG EVALUATION

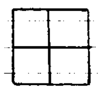
Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In.)	Max. Press. (psi)	Biaxial Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% Offset(ksi)	Elong.% in 2 In.	Uniaxial Ult.	Comments	Comments	Comments
	MIG									47.7	31.3	4.8				
	2219-T87/									44.5	28.9	4.0				
	2319									42.6	26.0	3.5				
										43.4	29.2	3.2				
BP-63		64A-4	11-27-64	Slight	12-17-64	1.57	215	37.5	12-18-64	42.3	29.5	3.5		Failed in Weld No. 1		
			12-10-64	Porosity												
										43.2	29.4	2.6				
										42.7	30.6	2.2				
										42.3	29.5	2.2				
BP-64	"	64A-4	11-27-64	OK	12-17-64	1.39	196	38.8	12-18-64	43.5	30.3	2.7		Failed in Weld No. 1		
			12-7-64	OK												
										40.9	28.9	2.3				
										42.4	27.4	2.8				
										41.5	27.4	3.2				
										41.9	29.3	3.1				
BP-72	"	64A-4	12-9-64	OK	12-17-64	1.59	206	36.7	12-18-64	41.8	28.4	2.5		Failed in Weld No. 2		
			12-10-64	OK												
Average						1.52	206	37.7		42.9	29.0	3.0	.88			

TABLE V (continued)

RESULTS FROM INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS FOR THE MIG AND TIG EVALUATION

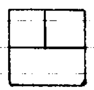
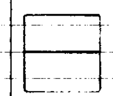
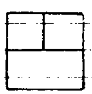
Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In.)	Max. Press. (psi)	Biaxial Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% Offset(ksi)	Elong.% in 2 In.	Uniaxial Ult.	Comments	Comments	Comments
	TIG									45.2	34.1	2.1				
	2219-T87/									42.8	30.9	1.7				
	2319									43.2	30.9	2.1				
										45.5	32.4	2.1				
BP-60		64A-2	11-12-64	OK	12-3-64	1.64	176	29.4	12-4-64	46.1	34.5	2.5		Failed in Weld No. 2		
			11-24-64	OK												
										45.1	30.0	3.0				
	MIG									40.5	26.8	2.0				
	2219-T87/									45.0	29.1	2.1				
	2319									45.2	28.0	3.6				
BP-65		64A-4	11-27-64	OK	12-17-64	1.41	201	39.8	12-18-64	42.0	28.4	2.1				
										41.7	37.1	2.3				
	MIG									44.3	36.6	2.3				
BP-70	2014-T6/	64A-3	12-2-64	OK	12-17-64	1.39	189	37.4	12-18-64	43.7	36.7	2.5		Failed in Weld No. 2		
	4043		12-9-64	OK												
																

TABLE VI

SUMMARY OF THE HYDRAULIC BULGE TEST AND UNIAXIAL TENSILE TEST DATA FOR VARIOUS WELD CONFIGURATIONS

Weld Configu-ration	Materials & Welding Process	Average Bulge Data				Average Uniaxial Tensile Data[c]				Biaxial / Uniaxial
		No. of Tests	Maximum Height (In.)	Maximum Pressure (psi)	Biaxial Ultimate (ksi)	No. of Tests	U. T. S. (ksi)	0.2% Y. S. (ksi)	Elongation % in 2 In.	
□	2014-T6 (Base Metal)	3	4.35	1130	77.1	10	70.8	65.0	11.2	1.09
□	2219-T87 "	3	4.20	993	70.5	10	66.8	54.9	10.9	1.06
	MIG 2014-T6/4043	3	1.28	142	30.9	37	42.1	35.5	1.7	.73
		3	1.36	170	35.2					.84
		3	1.18	128	30.4					.72
	TIG 2014-T6/4043	2[b]	1.49	190	35.1	39	47.9	39.6	1.9	.73
		3	1.45	184	34.9					.73
		3	1.42	181	35.2					.74
	TIG 2014-T6/2319	3	1.41	255	49.6	32	50.0	40.2	1.8	.99
		3	1.29	204	44.1					.88
		2[a]	1.45	228	43.1					.86
	MIG 2219-T87/2319	3	1.31	172	36.1	46	42.7	28.6	2.9	.85
		3	1.43	193	37.3					.87
		4	1.49	198	36.4					.85
	TIG 2219-T87/2319	3	1.23	171	38.2	48	43.5	33.4	1.8	.88
		3	1.49	182	33.7					.78
		3	1.41	174	33.7					.78

[a] One bulge test result invalid because of defect in weld.
[b] One bulge test invalid because of inoperative deflectometer.
[c] Average results from tests on specimens from all three weld configurations.

TABLE VII

SUMMARY OF BIAXIAL AND UNIAXIAL ULTIMATE STRENGTHS FOR MIG AND TIG WELDMENTS

Weldment Type	Biaxial				Uniaxial				Biaxial/Uniaxial
	No. of Tests	Ultimate Strength (ksi)	Standard Deviation (ksi)	99% Lower Tolerance Limit(ksi)	No. of Tests	Ultimate Strength (ksi)	Standard Deviation (ksi)	99% Lower Tolerance Limit (ksi)	
MIG 2014-T6/4043	9	32.1	2.76	20.7	37	42.1	4.14	29.9	0.76
TIG 2014-T6/4043	8	35.0	1.86	27.0	39	47.9	4.74	33.9	0.73
TIG 2014-T6/2319	8	45.9	3.54	30.5	32	50.0	2.84	41.4	0.92
MIG 2219-T87/2319	10	36.6	2.33	27.3	46	42.7	1.91	37.2	0.86
TIG 2219-T87/2319	9	35.3	3.13	22.3	48	43.5	2.20	37.2	0.81

TABLE VIII

RESULTS OF RESIDUAL STRESS MEASUREMENTS IN 1/8 INCH THICK, TIG AND MIG, 2219-T87/2319 WELDED PANELS

Panel No.	Location of Gages	Clamping Stress Maximum/Minimum/Direction[1] (ksi/ksi/Degrees) Strain Gage No. 1	No. 2	No. 3	Residual Stress Maximum/Minimum/Direction[1] (ksi/ksi/Degrees) Strain Gage No. 1	No. 2	No. 3
2-SG	Weld	14.3/4.9/82°	15.9/7.8/90°	14.8/11.5/75°	- - - -	14.6/-8.0/01°	3.5/-8.6/07°
3-SG	Weld	2.6/1.8/-65°	-0.3/0.1/-64°	- - - -	18.1/0.6/02°	19.8/-1.2/02°	- - - -
	Heat Affected						
	Base Metal	- - - -	1.6/0.8/90°	- - - -	- - - -	16.9/-0.6/00°	- - - -
4-SG	Weld	18.3/14.5/77°	22.2/7.1/-85°	4.8/2.8/-86°	13.0/2.9/00°	12.5/2.8/06°	20.1/5.1/02°
5-SG	Weld	-1.2/0.3/33°	1.9/1.6/61°	-1.2/0.6/29°	15.5/5.5/03°	16.6/7.1/08°	21.2/4.7/07°
	Heat Affected						
	Base Metal	- - - -	0.5/0.5/0°	- - - -	- - - -	-19.5/8.2/90°	- - - -
6-SG	Weld	-1.4/-0.1/-14°	1.6/0/17°	-2.8/0.4/-26°	18.9/-17.4/14°	18.2/-2.2/05°	22.3/0.3/01°
7-SG	Weld	2.9/-1.2/90°	3.8/-1.2/-75°	2.9/-2.7/-86°	15.2/-4.8/0°	12.5/-2.7/05°	18.3/2.5/08°
	Heat Affected						
	Base Metal	- - - -	7.3/2.3/90°	- - - -	- - - -	14.5/-10.6/0°	- - - -

1 Maximum refers to maximum principal stress.
Minimum refers to minimum principal stress.
Direction refers to direction of the maximum principal stress in relation to the center-line of the weld. Center-line of the weld is zero.

Note: Minus sign "-" refers to compressive stress. No sign means tensile stress.

TABLE IX

RESULTS OF INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS (EFFECTS OF STRESS RELIEF)

Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In.)	Max. Press. (psi)	Bia. Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% Offset(ksi)	Elong.% in 2 In.	Uniaxial Ult.	Comment	Comment	Comment
	2219-T87/ Base Metal									27.1	13.8	22.2				
										27.3	13.7	22.2				
										27.5	13.8	22.3				
										27.1	13.5	22.1				
BMA1	Annealed	--	--	--	11-13-64	7.95	475	23.6	11-13-64	27.0	13.4	22.6				
BMA2	"	--	--	--	11-13-64	7.55	482	24.2	11-13-64							
BMA3	"	--	--	--	11-13-64	7.10	485	25.4	11-13-64							
Average						7.53	481	24.3		27.2	13.6	22.3	.89			

TABLE IX (continued)

RESULTS OF INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS (EFFECTS OF STRESS RELIEF)

Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In)	Max. Press. (psi)	Bia. Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% offset(ksi)	Elong. % in 2 In.	Uniaxial Ult.	Comment	Comment	Comment
	TIG									27.7	12.8	19.6		1)Uniaxial tensile specimens		
	2219-T87/									27.4	13.1	18.2		failed in base metal.		
	2319									28.2	13.5	21.2				
										27.8	13.6	19.2		2)Bulge panel failed		
BP-40		64A-2	10-5-64	OK	10-21-64	6.00	476	23.8	10-22-64	26.8	12.5	18.3		transverse to weld.		
	Annealed															
										27.4	13.1	19.3		1)Uniaxial tensile specimens		
										27.0	12.9	19.8		failed in base metal.		
										28.0	13.4	19.2				
										27.7	13.0	19.3		2)Bulge panel failed		
BP-41	"	64A-2	10-5-64	OK	10-21-64	5.90	440	21.9	10-22-64	28.1	13.4	20.1		transverse to weld.		
										27.3	13.2	19.5		1)Uniaxial tensile specimens		
										27.4	12.9	19.8		failed in base metal.		
										28.3	13.6	19.8				
										27.8	13.4	17.2		2)Bulge panel failed parallel to		
BP-42	"	64A-2	10-6-64	OK	10-21-64	4.95	430	24.2	10-22-64	27.9	13.2	19.7		weld in base metal*		
Average						5.62	449	23.3		27.6	13.2	19.3	.84			

*Stencil marks in the base metal probably caused the panel to fail in the base metal parallel to the weld.

TABLE IX (continued)

RESULTS OF INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS (EFFECTS OF STRESS RELIEF)

Panel Identification		Welding	Date	Radiograph	Bulge Data				Uniaxial Tensile Data				Biaxial Ult.			
Number	Description	Procedure	Welded	Results	Date Tested	Bulge Ht. (In)	Max. Press. (psi)	Bia. Ult. (ksi)	Date Tested	U.S. (ksi)	Y.S. 0.2% offset(ksi)	Elong.% in 2 In.	Uniaxial Ult.	Comment	Comment	Comment
	TIG									37.2	-	3.8		Failures of both uniaxial tensile		
	2219-T87/									39.1	27.4	3.3		specimens and bulge panel		
	2319									40.4	28.0	2.6		occurred in the weld metal.		
										39.4	25.6	3.6				
BP-44		64A-2	10-8-64	OK	10-21-64	1.35	166	33.9	10-22-64	38.6	25.0	3.3				
	Weld Crowns															
	Removed															
										40.4	26.7	2.5		Failures of both uniaxial tensile		
										40.3	27.2	3.0		specimens and bulge panel		
										40.3	25.9	3.3		occurred in the weld metal.		
										40.6	26.5	3.3				
BP-45	"	64A-2	10-8-64	OK	10-21-64	1.30	174	36.9	10-22-64	40.5	27.1	2.4				
										40.2	28.0	2.9		Failures of both uniaxial tensile		
										40.0	27.9	3.0		specimens and bulge panel		
										40.0	26.0	3.3		occurred in the weld metal.		
										40.3	27.7	3.3				
BP-46	"	64A-2	10-8-64	OK	10-21-64	1.27	156	33.9	10-22-64	40.3	27.0	3.3				
Average						1.31	165	34.9		39.8	26.8	3.2	.88			

TABLE IX (continued)

RESULTS OF INDIVIDUAL HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS (EFFECTS OF STRESS RELIEF)

Panel Identification Number	Panel Identification Description	Welding Procedure	Date Welded	Radiograph Results	Bulge Data: Date Tested	Bulge Data: Bulge Ht. (In)	Bulge Data: Max. Press. (psi)	Bulge Data: Bia. Ult. (ksi)	Uniaxial Tensile Data: Date Tested	Uniaxial Tensile Data: U.S. (ksi)	Uniaxial Tensile Data: Y.S. 0.2% offset(ksi)	Uniaxial Tensile Data: Elong. % in 2 In.	Biaxial Ult. / Uniaxial Ult.	Comment	Comment	Comment
	TIG									43.8	25.8	2.7		Uniaxial tensile specimens and		
	2219-T87/									45.3	28.4	2.7		bulged panel failed in both		
	2319									45.0	27.2	2.9		fusion line and weld metal.		
										46.1	28.3	3.0				
BP-47		64A-5	10-9-64	OK	10-23-64	1.70	222	35.7	10-22-64	44.0	29.1	2.2				
	Multipass															
										45.7	26.8	3.5		Uniaxial tensile specimens and		
										45.2	28.5	3.5		bulged panel failed in both		
										46.9	27.3	4.0		fusion line and weld metal.		
										46.2	28.7	4.0				
BP-48	"	64A-5	10-9-64	OK	10-23-64	1.50	216	39.6	10-23-64	45.8	28.7	3.4				
										43.6	28.3	2.5		Uniaxial tensile specimens and		
										45.8	29.1	3.3		bulged panel failed in both		
										45.2	27.5	3.4		fusion line and weld metal.		
BP-50	"	64A-5	10-9-64	OK	10-23-64	1.52	212	38.2	10-23-64	45.9	27.7	3.4				
Average						1.57	217	37.8		45.2	28.0	3.2	.84			

TABLE X

RESULTS OF HYDRAULIC BULGE TESTS AND UNIAXIAL TENSILE TESTS
RUN TO STUDY BIAXIAL/UNIAXIAL RATIO

Panel Description	Average Bulge Test Data				Average Uniaxial Tensile Data				
	No. of Tests	Bulge Height (Inches)	Max. Press. (psi)	Biaxial U.S. (ksi)	No. of Tests	U.S. (ksi)	Y.S. 0.2% Offset (ksi)	Elong. % in 2 Inches	Biaxial Ult / Uniaxial Ult.
TIG 2219-T87/ 2319 Single weld As-welded	3	1.23	171	38.5	18	43.7	35.1	1.8	.88
2219-T87 Base Metal Annealed	3	7.53	481	24.3	5	27.2	13.6	22.3	.89
TIG 2219-T87/ 2319 Single weld Annealed	3	5.62	449	23.3	15	27.6	13.2	19.3	.84
TIG 2219-T87/ 2319 Single weld Weld Crowns Removed	3	1.31	165	34.9	15	39.8	26.8	3.2	.88
TIG 2219-T87/ 2319 Single weld Multipass	3	1.57	217	37.8	14	45.2	28.0	3.2	.84

TABLE XI

X7106-T63 MECHANICAL PROPERTIES

Thickness (Inch)	Grain Direction		Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation Percent (in 2 inches)
.090	Long.		54.7	60.7	11.7
			53.9	60.1	11.2
			54.3	60.0	11.2
			53.7	59.4	11.8
			53.6	59.4	11.5
		AV.	54.0	59.9	11.5
.090	Trans.		55.6	62.4	10.2
			56.0	62.8	10.7
			55.9	62.8	10.7
			55.3	62.1	10.2
			55.6	62.4	10.5
		AV.	55.7	62.5	10.5
.187	Long.		61.0	67.8	11.2
			61.3	68.3	10.0
			60.7	67.8	11.0
			60.9	67.8	11.2
			61.0	68.1	11.1
		AV.	61.0	68.0	10.9
.187	Trans.		59.0	66.1	11.6
			58.6	65.7	12.5
			58.8	66.2	12.5
			58.9	65.7	13.3
			58.8	65.7	12.0
		AV.	58.8	65.9	12.3

TABLE XI (continued)

X7106-T63 MECHANICAL PROPERTIES

Thickness (Inch)	Grain Direction		Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation Percent (in 2 inches)
.500	Long.		59.0	64.6	17.7
			60.1	65.8	17.8
			58.5	64.4	17.8
			59.1	65.0	17.8
			58.8	64.8	17.5
		AV.	59.1	64.9	17.7
.500	Trans.		58.5	64.2	16.6
			58.9	64.4	17.0
			58.8	64.3	15.2
			59.1	64.3	15.7
			58.7	64.2	15.7
		AV.	58.8	64.3	16.0
1.00	Long.		58.1	64.1	20.7
			58.4	64.5	20.9
			57.9	64.0	20.9
			58.8	64.9	20.7
			58.4	64.3	20.5
		AV.	58.3	64.4	20.7
1.00	Trans.		56.0	61.9	19.4
			56.2	62.2	19.1
			56.1	62.1	19.4
			56.1	61.9	19.9
			56.2	62.1	19.3
		AV.	56.1	62.0	19.4

TABLE XII

SUMMARY OF X7106-T63 MECHANICAL PROPERTIES

Thickness (Inch)	Grain Direction	Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation % (2 Inches)	Hardness Rb
.090	Long.	54.0	59.9	11.5	79.5
	Trans.	55.7	62.5	10.5	
.187	Long	61.0	68.0	10.9	80.0
	Trans.	58.8	65.9	12.3	
.500	Long.	59.1	64.9	17.7	76.5
	Trans.	58.8	64.3	16.0	
1.00	Long.	58.3	64.4	20.7	74.5
	Trans.	56.1	62.0	19.4	

TABLE XIII

MECHANICAL PROPERTIES OF .090 INCH THICK X7106-T63/X5180 (PANEL A) WELDMENT AFTER VARIOUS NATURAL AGING TIMES

Naturally Aged		Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation Percent (in 2 Inches)	Fracture Location
1 Day		31.3	46.0	5.3	Heat Affected Base Metal
1 Day		30.1	46.0	5.9	Heat Affected Base Metal
1 Day		31.1	45.6	3.0	Fusion Line
1 Day		31.3	45.2	3.3	Fusion Line
1 Day		31.2	45.7	3.3	Fusion Line
	AV.	31.0	45.7	4.2	
1 Week		34.8	49.9	3.1	Heat Affected Base Metal
1 Week		35.8	50.9	3.7	Fusion Line
1 Week		36.8	49.9	2.7	Fusion Line
1 Week		36.5	51.1	4.9	Heat Affected Base Metal
1 Week		35.9	51.6	4.9	Heat Affected Base Metal
	AV.	36.0	50.7	3.9	
2 Weeks		37.5	52.6	4.8	Heat Affected Base Metal
2 Weeks		36.6	52.4	4.8	Heat Affected Base Metal
2 Weeks		37.2	52.0	2.9	Fusion Line
2 Weeks		39.1	52.3	3.8	Heat Affected Base Metal
2 Weeks		37.6	52.1	4.3	Heat Affected Base Metal
	AV.	37.6	52.3	4.1	
4 Weeks		37.2	51.6	2.2	Fusion Line
4 Weeks		38.5	52.9	5.6	Heat Affected Base Metal
4 Weeks		38.0	53.1	4.3	Heat Affected Base Metal
4 Weeks		38.6	53.1	5.1	Heat Affected Base Metal
4 Weeks		39.1	53.0	4.6	Heat Affected Base Metal
	AV.	38.3	52.7	4.4	
8 Weeks		41.1	52.3	3.9	Heat Affected Base Metal
8 Weeks		41.6	51.3	2.7	Fusion Line
8 Weeks		39.4	52.4	4.1	Heat Affected Base Metal
8 Weeks		39.5	53.3	4.8	Heat Affected Base Metal
8 Weeks		39.4	53.2	4.3	Heat Affected Base Metal
	AV.	40.2	52.5	3.9	

TABLE XIII (Continued)

MECHANICAL PROPERTIES OF .090 INCH THICK X7106-T63/X5180 (PANEL B) WELDMENT AFTER VARIOUS NATURAL AGING TIMES

Naturally Aged	Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation Percent (in 2 Inches)	Fracture Location
1 Day	30.5	46.5	5.5	Fusion Line
1 Day	31.2	46.5	4.5	Fusion Line
1 Day	30.7	46.9	5.1	Fusion Line
1 Day	30.7	46.6	4.5	Fusion Line
1 Day	30.6	46.3	5.1	Fusion Line
	AV. 30.7	46.6	4.9	
1 Week	35.2	50.9	4.7	Heat Affected Base Metal
1 Week	35.7	50.2	3.6	Fusion Line
1 Week	36.2	50.0	3.6	Fusion Line
1 Week	37.3	51.1	4.1	Heat Affected Base Metal
1 Week	35.0	50.4	5.6	Heat Affected Base Metal
	AV. 35.9	50.5	4.4	
2 Weeks	37.5	52.0	4.7	Heat Affected Base Metal
2 Weeks	38.0	52.3	4.3	Heat Affected Base Metal
2 Weeks	38.2	52.8	4.6	Heat Affected Base Metal
2 Weeks	36.4	51.5	5.3	Heat Affected Base Metal
2 Weeks	36.4	52.0	5.0	Heat Affected Base Metal
	AV. 37.3	52.1	4.8	
4 Weeks	36.8	53.0	5.6	Heat Affected Base Metal
4 Weeks	37.1	52.2	5.2	Heat Affected Base Metal
4 Weeks	39.0	53.5	5.2	Heat Affected Base Metal
4 Weeks	39.1	53.6	4.7	Heat Affected Base Metal
4 Weeks	38.9	53.3	4.7	Heat Affected Base Metal
	AV. 38.2	53.1	5.1	
8 Weeks	40.4	52.7	4.4	Heat Affected Base Metal
8 Weeks	38.7	52.0	5.2	Heat Affected Base Metal
8 Weeks	39.0	53.2	4.7	Heat Affected Base Metal
8 Weeks	39.1	52.3	4.8	Heat Affected Base Metal
8 Weeks	37.9	52.0	4.5	Heat Affected Base Metal
	AV. 39.0	52.5	4.7	

TABLE XIII (Continued)

MECHANICAL PROPERTIES OF .090 INCH THICK X7106-T63/5356 (PANEL C) WELDMENT AFTER VARIOUS NATURAL AGING TIMES

Naturally Aged	Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation Percent (in 2 Inches)	Fracture Location
1 Day	27.3	43.6	5.1	Fusion Line
1 Day	30.1	44.3	3.5	Fusion Line
1 Day	30.0	45.1	4.4	Fusion Line
1 Day	28.9	45.5	6.0	Heat Affected Base Metal
1 Day	29.5	44.8	4.3	Fusion Line
	AV. 29.2	44.6	4.7	
1 Week	34.2	51.3	5.1	Heat Affected Base Metal
1 Week	34.0	50.8	4.4	Fusion Line
1 Week	34.1	50.6	4.0	Fusion Line
1 Week	35.7	51.1	4.8	Heat Affected Base Metal
1 Week	36.8	51.3	4.5	Heat Affected Base Metal
	AV. 35.0	51.0	4.6	
2 Weeks	36.4	52.0	3.5	Fusion Line
2 Weeks	37.5	52.3	4.3	Heat Affected Base Metal
2 Weeks	36.5	50.6	4.8	Heat Affected Base Metal
2 Weeks	35.3	52.5	7.1	Heat Affected Base Metal
2 Weeks	35.9	49.9	2.9	Fusion Line
	AV. 36.3	51.5	4.5	
4 Weeks	38.0	53.1	4.7	Heat Affected Base Metal
4 Weeks	37.9	53.6	4.5	Heat Affected Base Metal
4 Weeks	38.0	52.0	3.2	Fusion Line
4 Weeks	39.7	52.6	3.2	Fusion Line
4 Weeks	36.4	50.3	2.9	Fusion Line
	AV. 38.0	52.3	3.7	
8 Weeks	39.5	52.8	3.2	Fusion Line
8 Weeks	39.4	53.2	5.0	Heat Affected Base Metal
8 Weeks	37.3	52.0	4.6	Fusion Line
8 Weeks	38.5	53.1	5.4	Heat Affected Base Metal
8 Weeks	38.8	52.5	4.0	Heat Affected Base Metal
	AV. 38.7	52.7	4.4	

TABLE XIII (Continued)

MECHANICAL PROPERTIES OF .090 INCH THICK X7106-T63/5556 (PANEL D) WELDMENT AFTER VARIOUS NATURAL AGING TIMES

Naturally Aged	Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation Percent (in 2 Inches)	Fracture Location
1 Day	32.3	45.8	3.8	Heat Affected Base Metal
1 Day	32.9	43.2	3.4	Heat Affected Base Metal
1 Day	33.3	45.7	4.4	Heat Affected Base Metal
1 Day	33.8	46.3	4.5	Heat Affected Base Metal
1 Day	33.9	46.3	4.4	Heat Affected Base Metal
	AV. 33.2	45.4	4.1	
1 Week	37.6	51.1	4.7	Heat Affected Base Metal
1 Week	36.6	49.5	4.9	Heat Affected Base Metal
1 Week	37.6	51.0	4.7	Heat Affected Base Metal
1 Week	38.5	50.9	4.0	Heat Affected Base Metal
1 Week	36.5	50.2	3.9	Heat Affected Base Metal
	AV. 37.4	50.5	4.4	
2 Weeks	38.7	51.9	4.7	Heat Affected Base Metal
2 Weeks	37.9	51.3	3.6	Fusion Line
2 Weeks	38.1	53.3	3.8	Heat Affected Base Metal
2 Weeks	37.6	51.0	3.0	Fusion Line
2 Weeks	36.9	52.3	5.0	Heat Affected Base Metal
	AV. 37.8	52.0	4.0	
4 Weeks	39.1	52.5	5.6	Heat Affected Base Metal
4 Weeks	39.1	51.1	2.9	Fusion Line
4 Weeks	38.6	53.1	5.3	Heat Affected Base Metal
4 Weeks	38.5	51.2	2.5	Weld
4 Weeks	38.7	53.1	4.7	Heat Affected Base Metal
	AV. 38.8	52.2	4.2	
8 Weeks	37.9	52.1	5.4	Heat Affected Base Metal
8 Weeks	39.2	51.6	3.8	Fusion Line
8 Weeks	39.0	51.6	4.5	Heat Affected Base Metal
8 Weeks	38.6	51.5	3.3	Fusion Line
8 Weeks	38.6	53.0	4.8	Heat Affected Base Metal
	AV. 38.7	52.0	4.4	

TABLE XIV

SUMMARY OF MECHANICAL PROPERTIES OF .090 INCH X7106-T63 WELDMENTS AFTER VARIOUS NATURAL AGING TIMES

Panel	Filler Metal	Aging Time	Yield Strength, ksi (0.2% Offset)	Ultimate Strength, ksi	Elongation Percent (in 2 inches)	Percent Failures Located in Heat Affected Base Metal
A	X5180	1 Day	31.0	45.7	4.2	40
		1 Week	36.0	50.7	3.9	60
		2 Weeks	37.6	52.3	4.1	80
		4 Weeks	38.3	52.7	4.4	80
		8 Weeks	40.2	52.5	3.9	80
B	X5180	1 Day	30.7	46.6	4.9	0
		1 Week	35.9	50.5	4.4	60
		2 Weeks	37.3	52.1	4.8	100
		4 Weeks	38.2	53.1	5.1	100
		8 Weeks	39.0	52,5	4.7	100
C	5356	1 Day	29.2	44.6	4.7	20
		1 Week	35.0	51.0	4.6	60
		2 Weeks	36.3	51.5	4.5	60
		4 Weeks	38.0	52.3	3.7	40
		8 Weeks	38.7	52.7	4.4	60
D	5556	1 Day	33.2	45.4	4.1	100
		1 Week	37.4	50.5	4.4	100
		2 Weeks	37.8	52.0	4.0	60
		4 Weeks	38.8	52.2	4.2	60
		8 Weeks	38.7	52.0	4.4	60

FIGURES

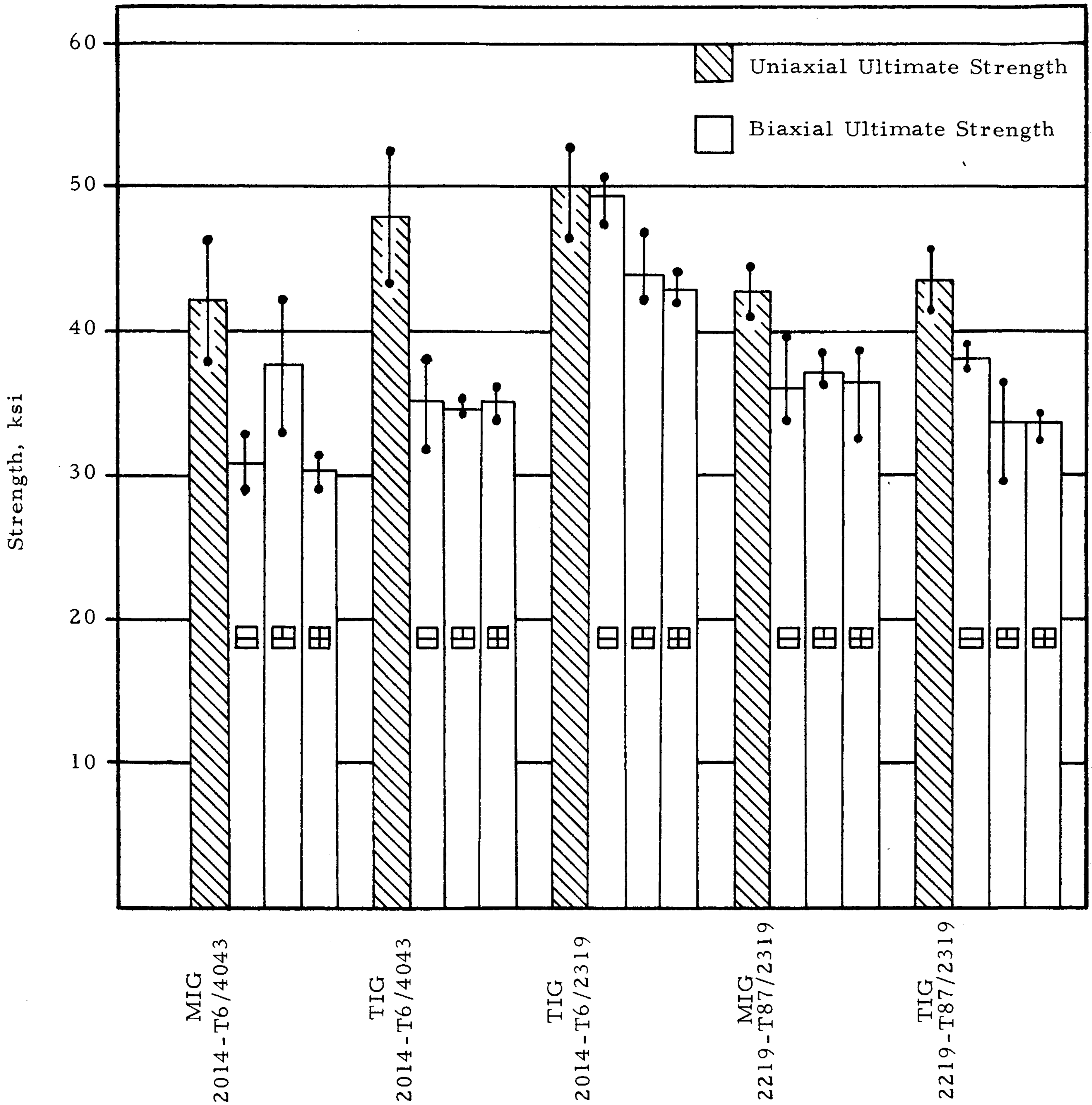


FIGURE 1. AVERAGE UNIAXIAL AND BIAXIAL ULTIMATE STRENGTHS FOR VARIOUS WELD CONFIGURATIONS

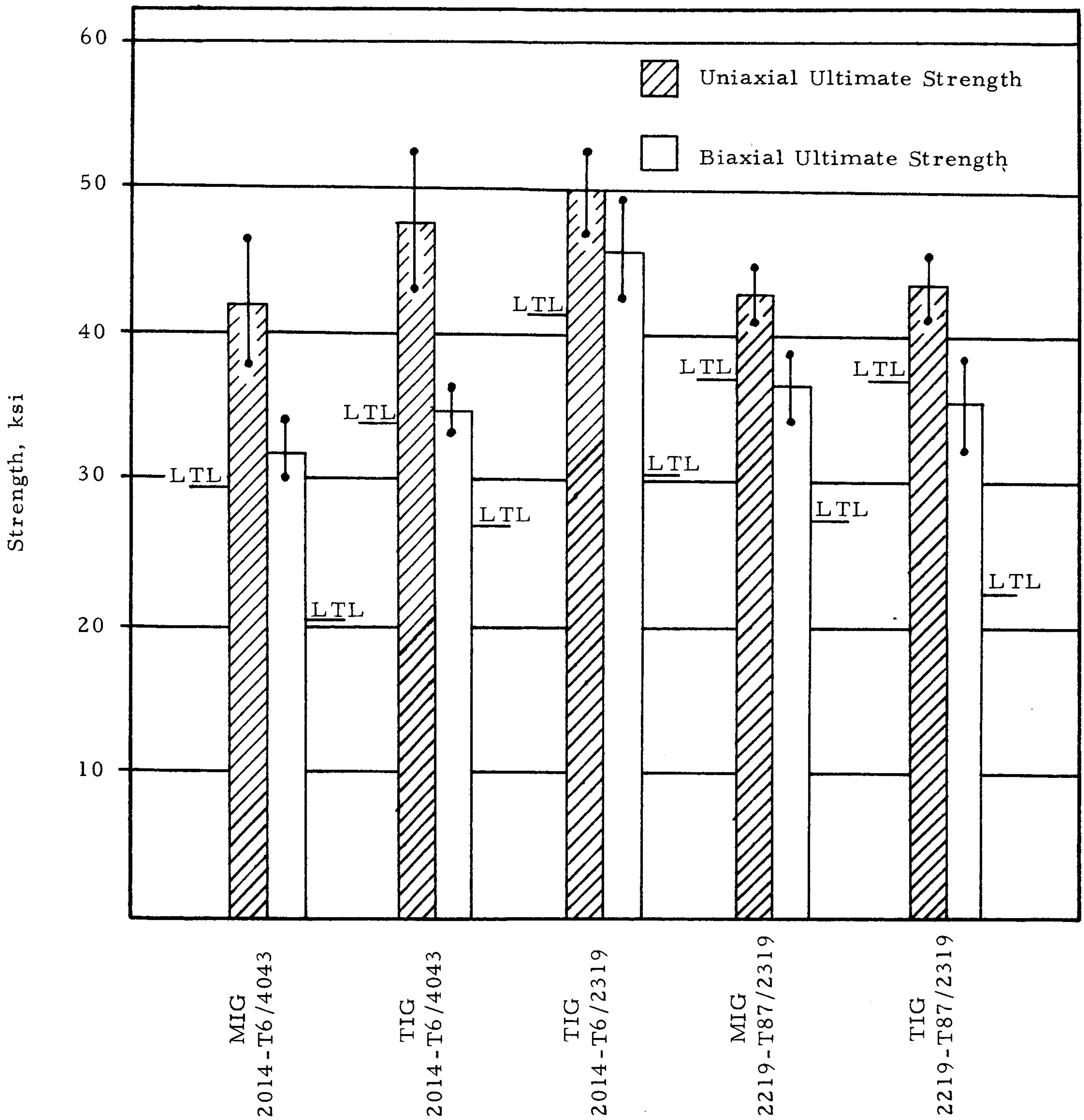


FIGURE 2. AVERAGE UNIAXIAL AND BIAXIAL ULTIMATE STRENGTH FOR MIG AND TIG WELDMENTS

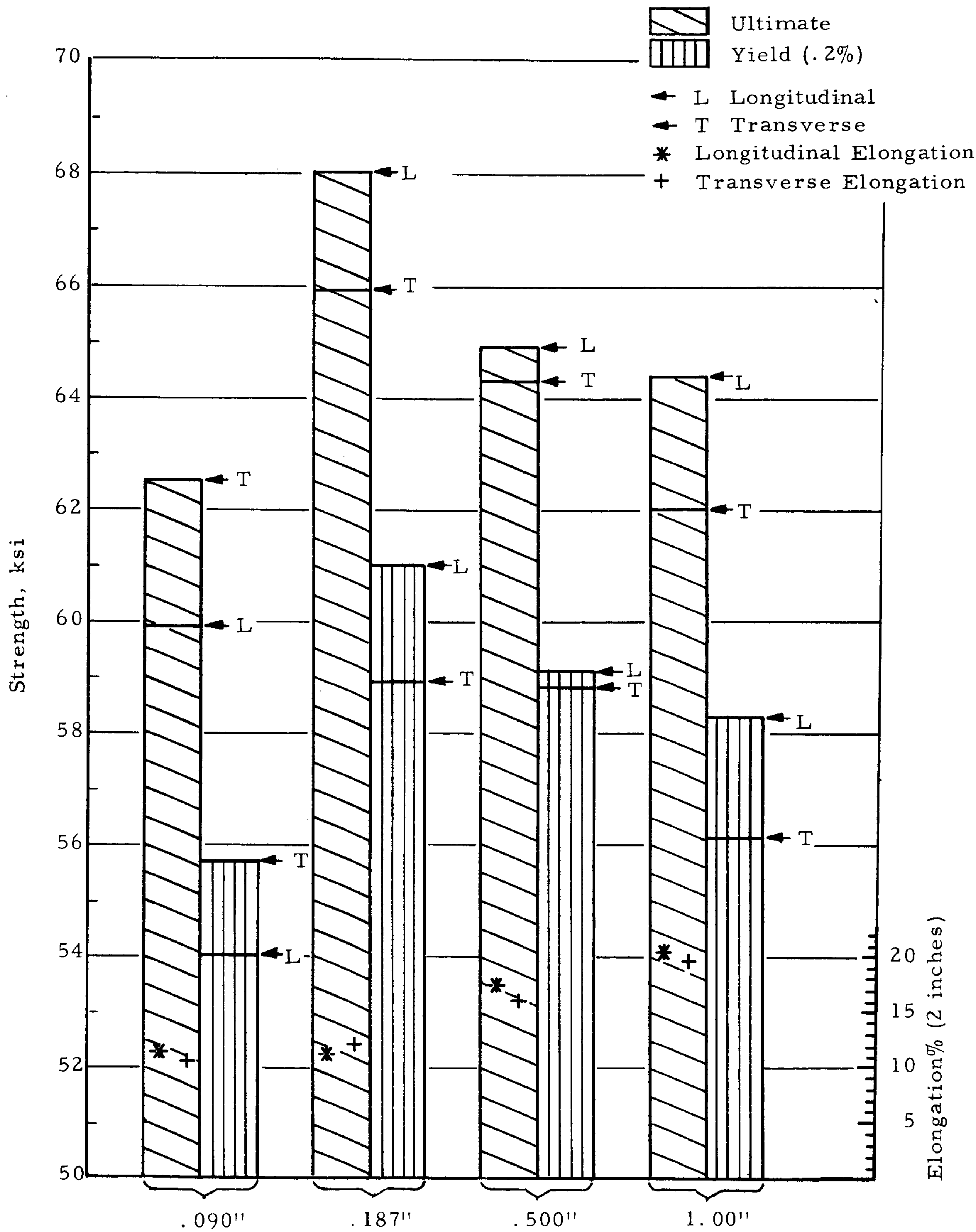
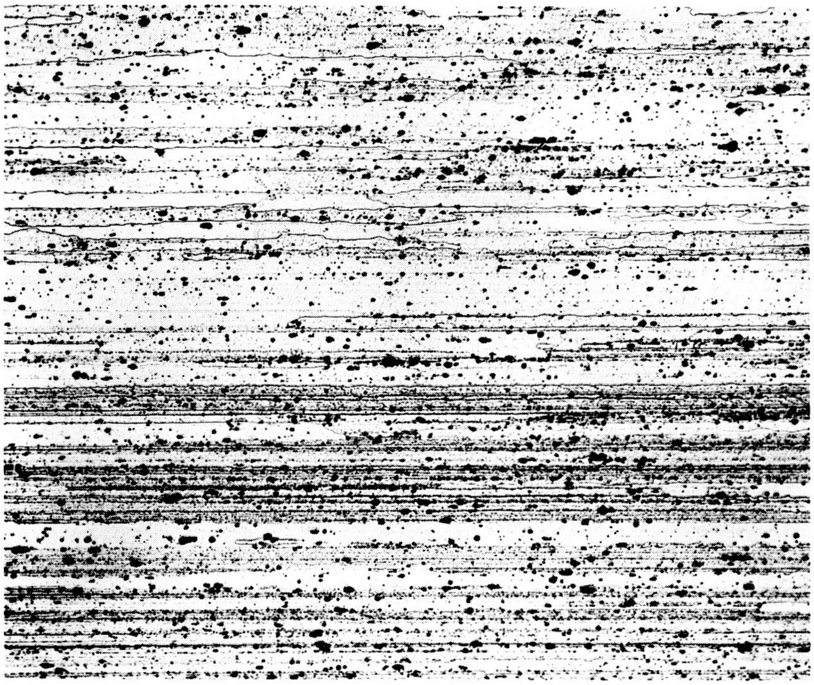
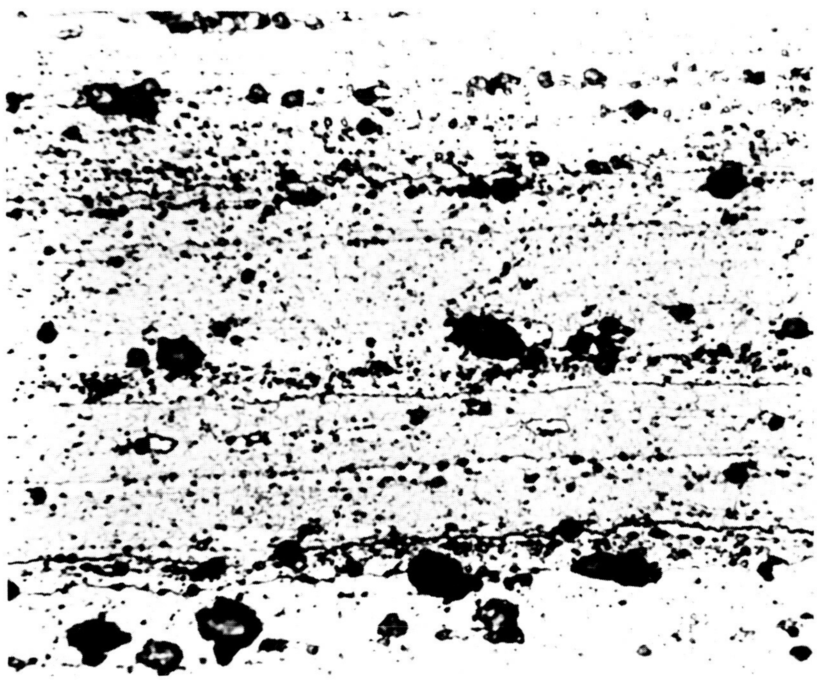


FIGURE 3. BAR GRAPH OF MECHANICAL PROPERTIES OF VARIOUS THICKNESSES OF X7106-T63



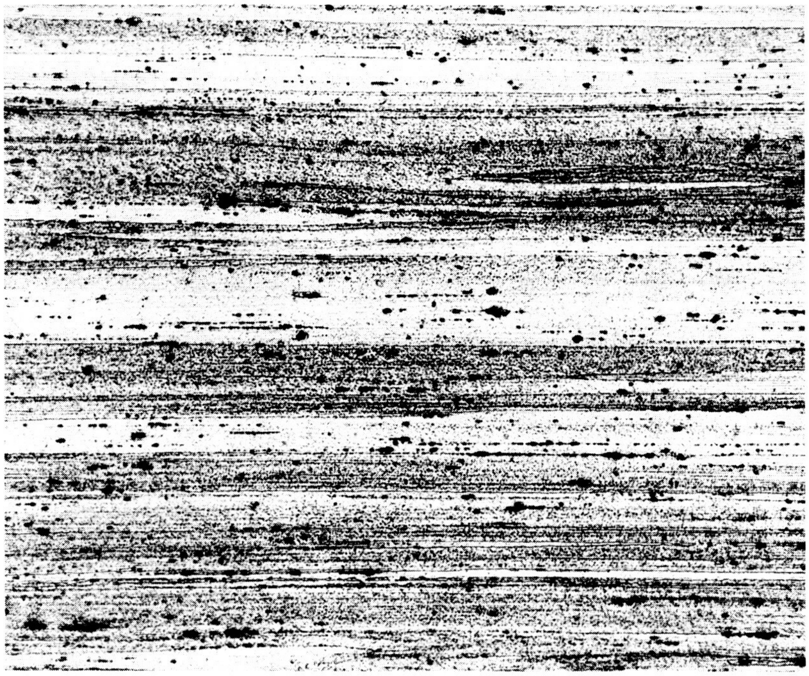
100X



Etchant-Keller's

1500X

FIGURE 4. MICROSTRUCTURE OF X7106-T63
.090 INCH SHEET



100X

Etchant Keller's 1500X

FIGURE 5. MICROSTRUCTURE OF X7106-T63
1.00 INCH PLATE

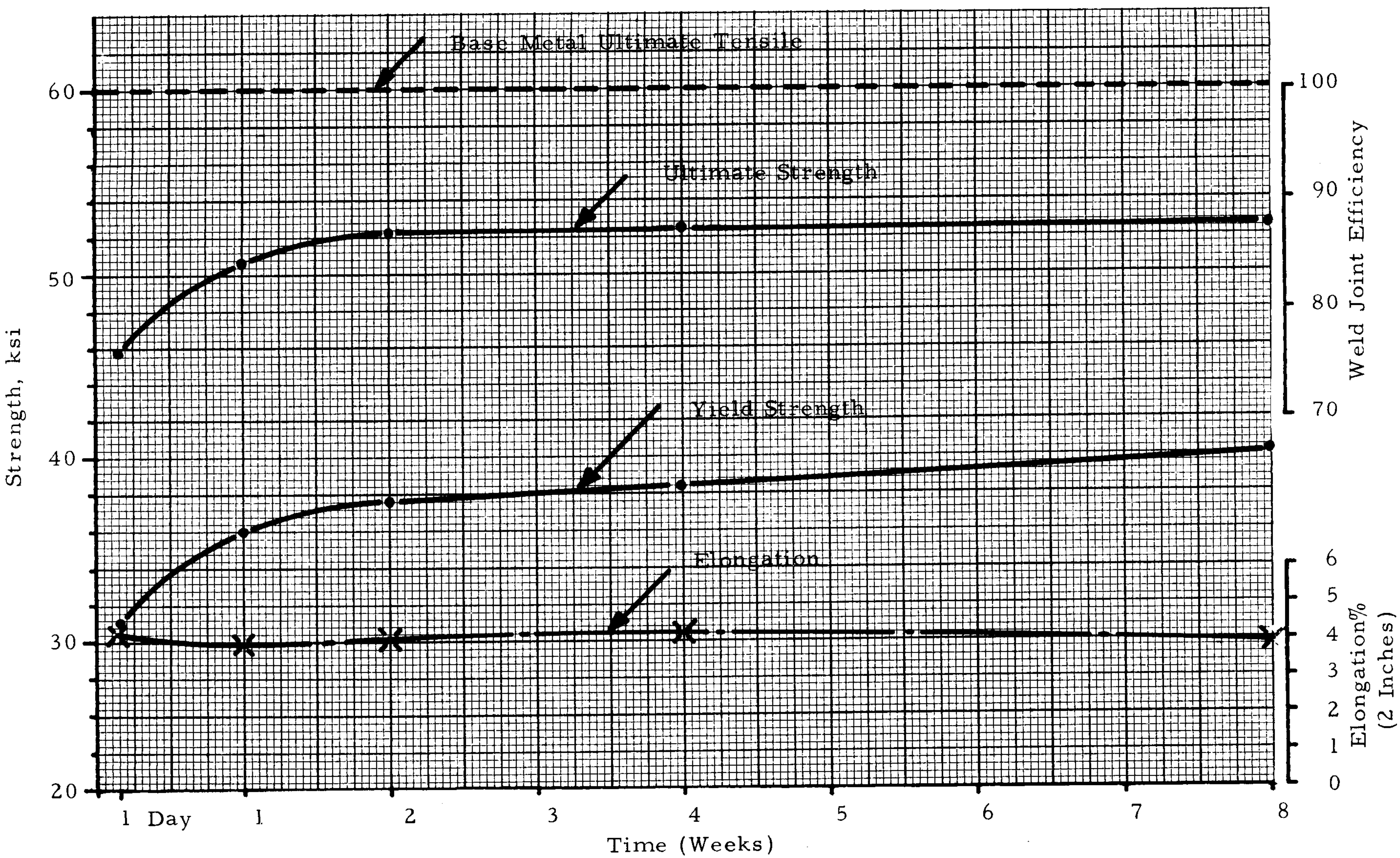


FIGURE 6. MECHANICAL PROPERTIES OF X7106/X5180 WELDMENTS (PANEL A) AFTER NATURAL AGING

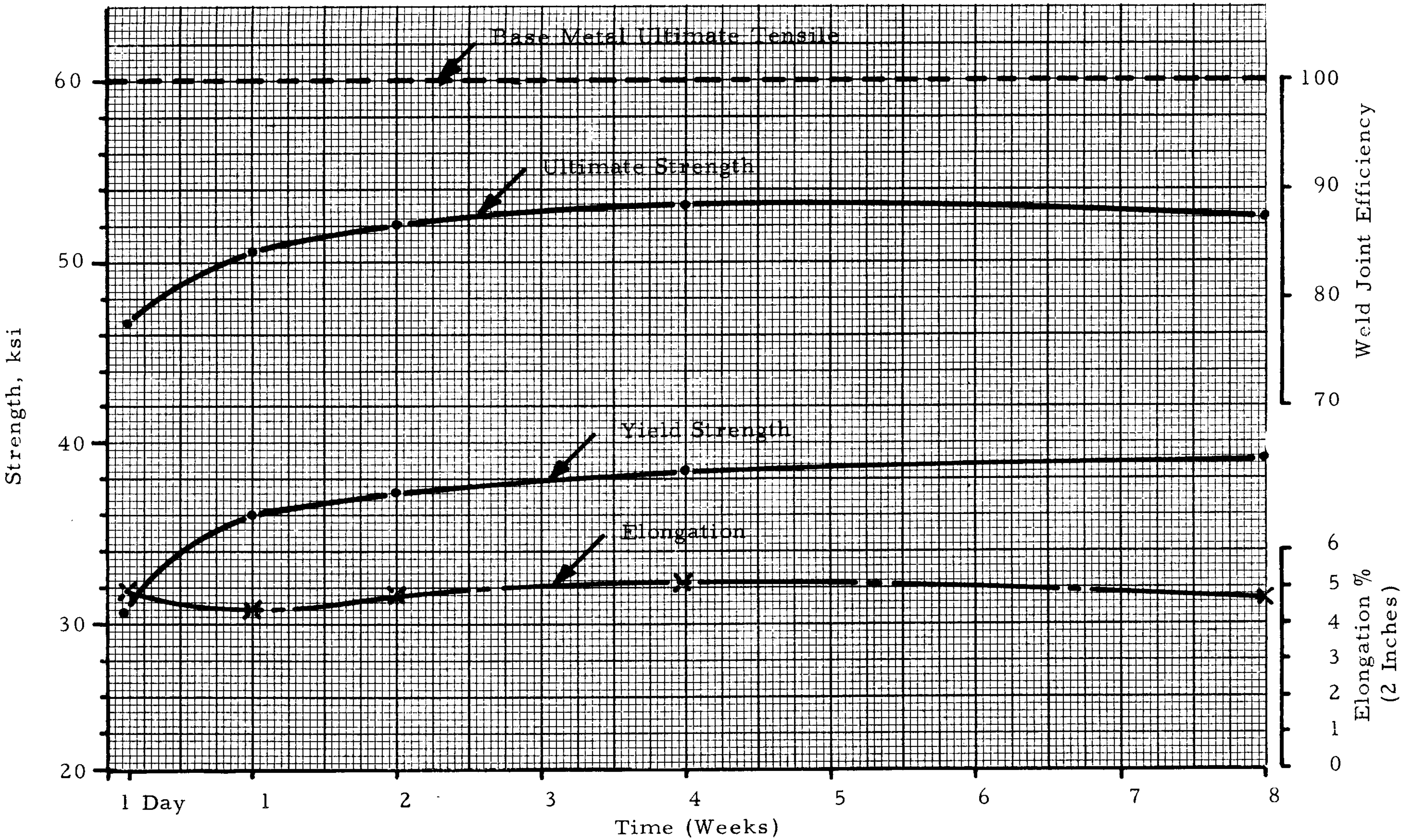


FIGURE 7. MECHANICAL PROPERTIES OF X7106/X5180 WELDMENTS (PANEL B) AFTER NATURAL AGING

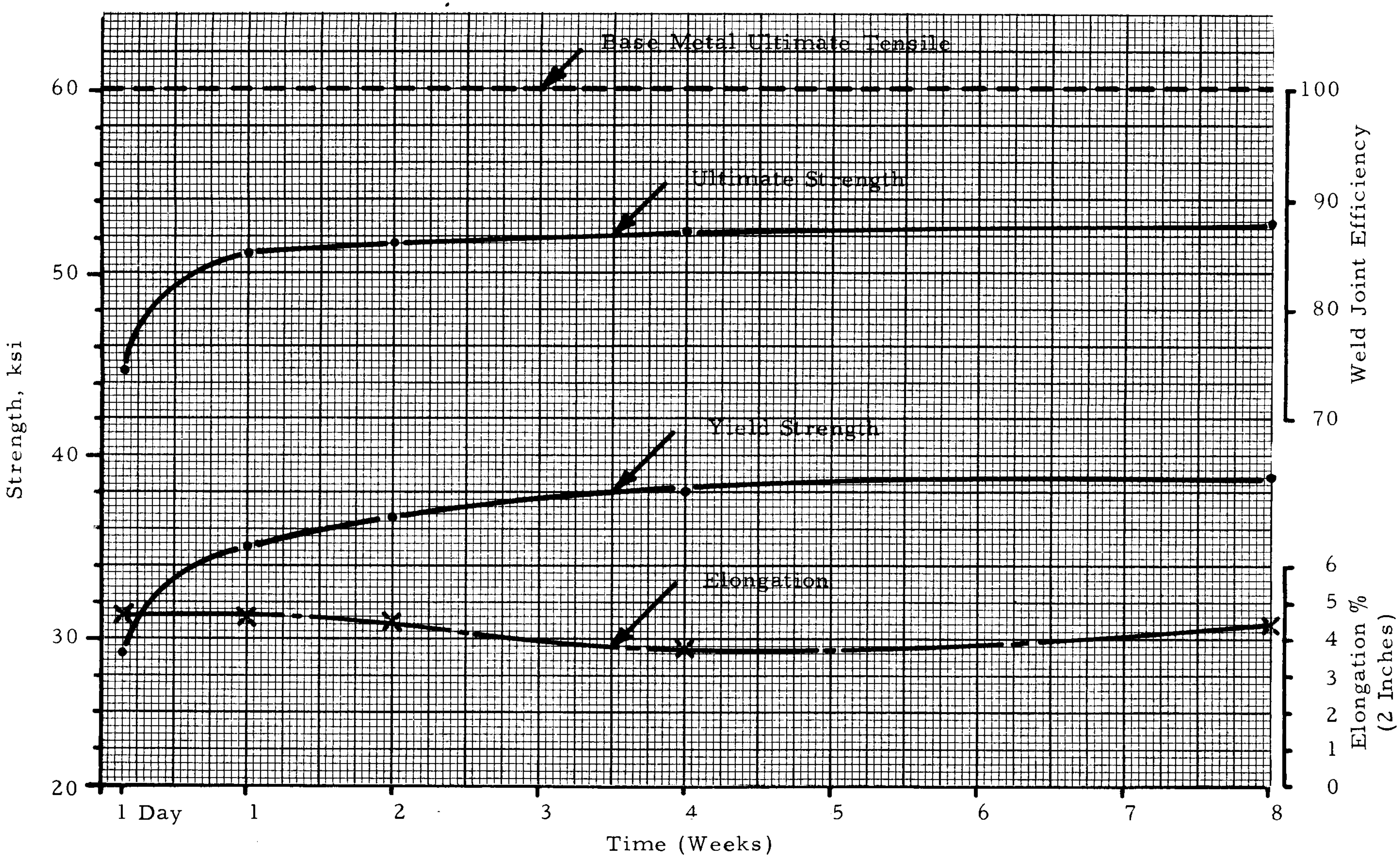


FIGURE 8. MECHANICAL PROPERTIES OF X7106/5356 WELDMENTS AFTER NATURAL AGING

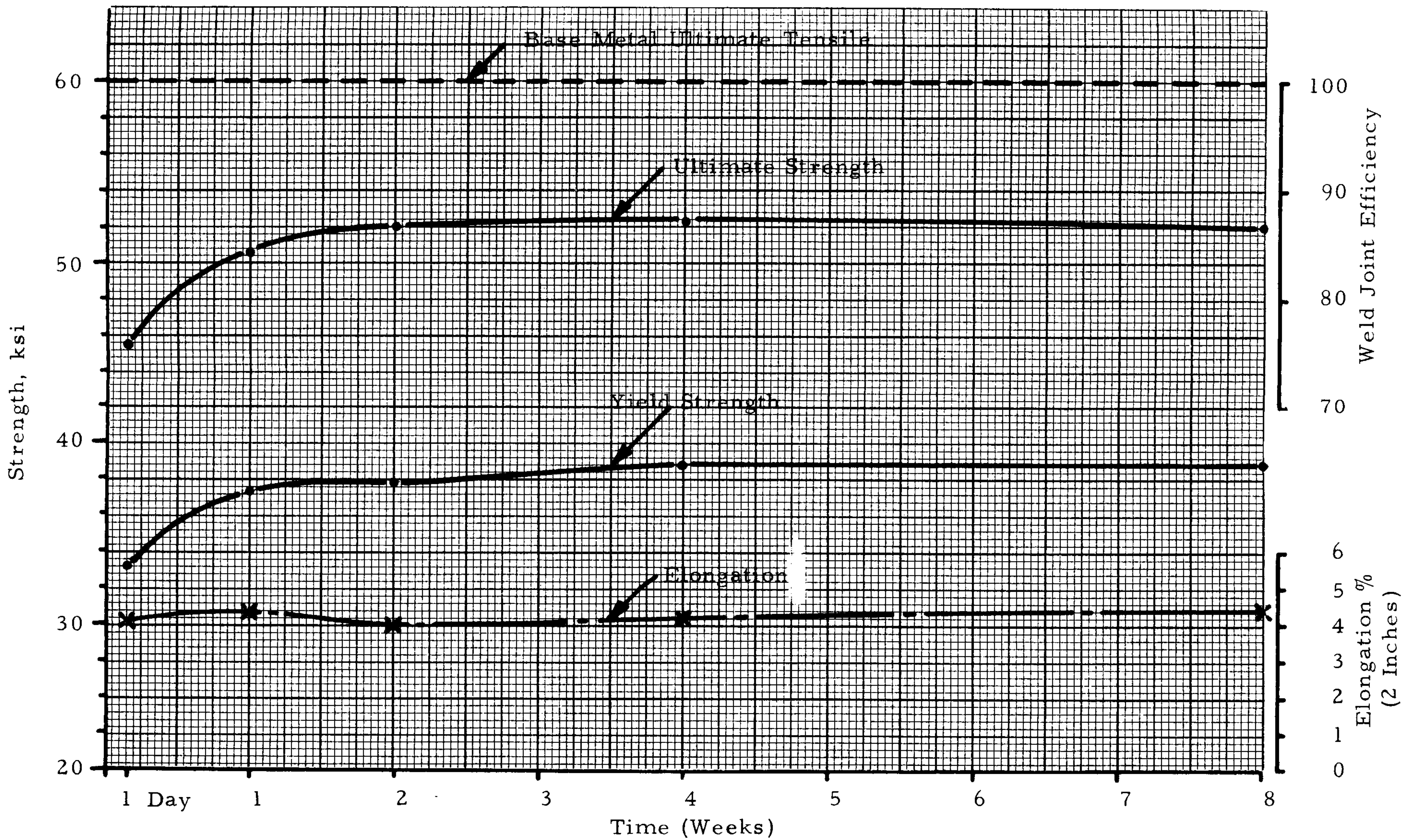


FIGURE 9. MECHANICAL PROPERTIES OF X7106/5556 WELDMENTS AFTER NATURAL AGING

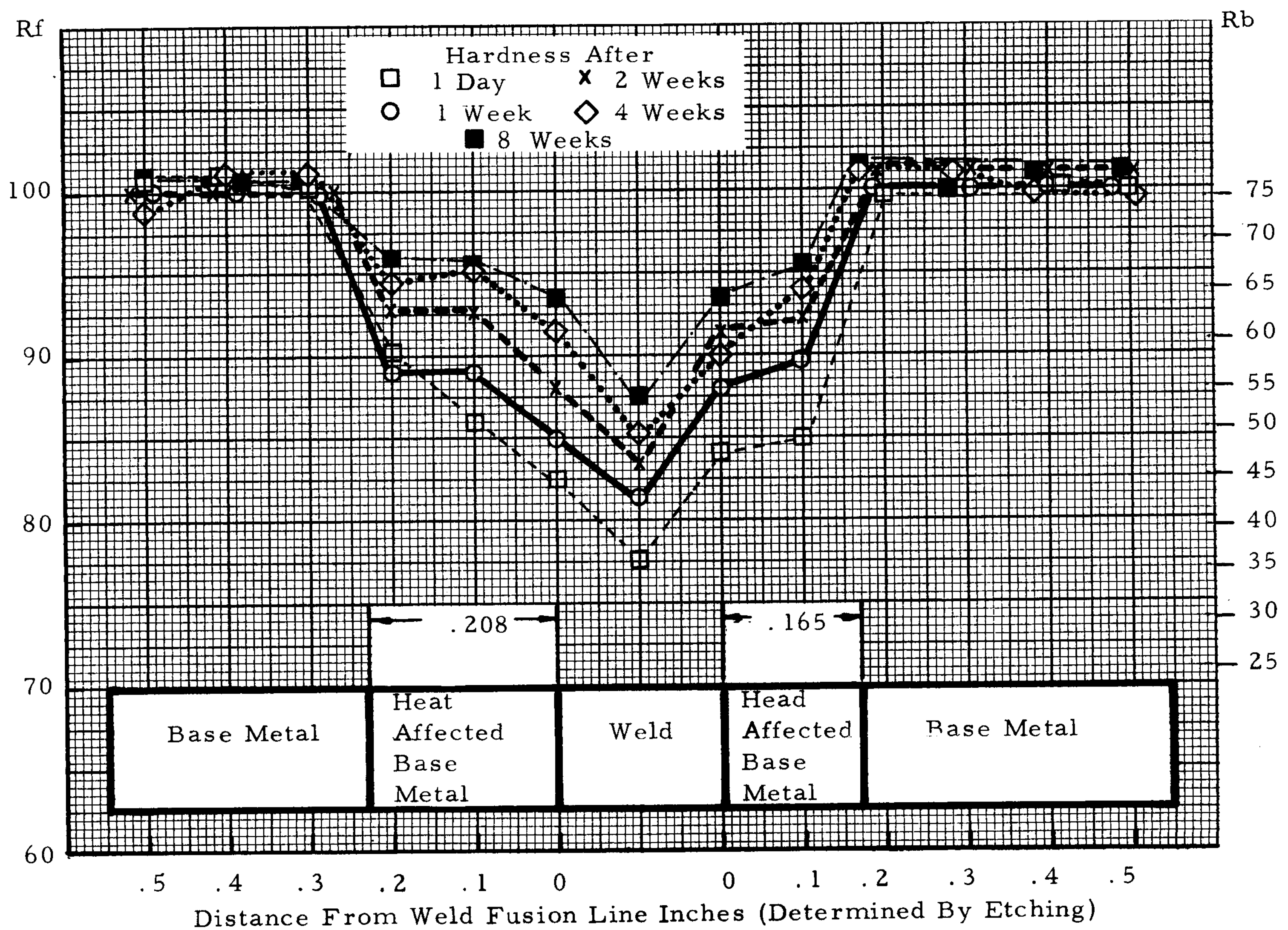


FIGURE 10. HARDNESS SURVEYS OF X7106/X5180 WELDMENT AFTER VARIOUS NATURAL AGING TIMES (PANEL B)

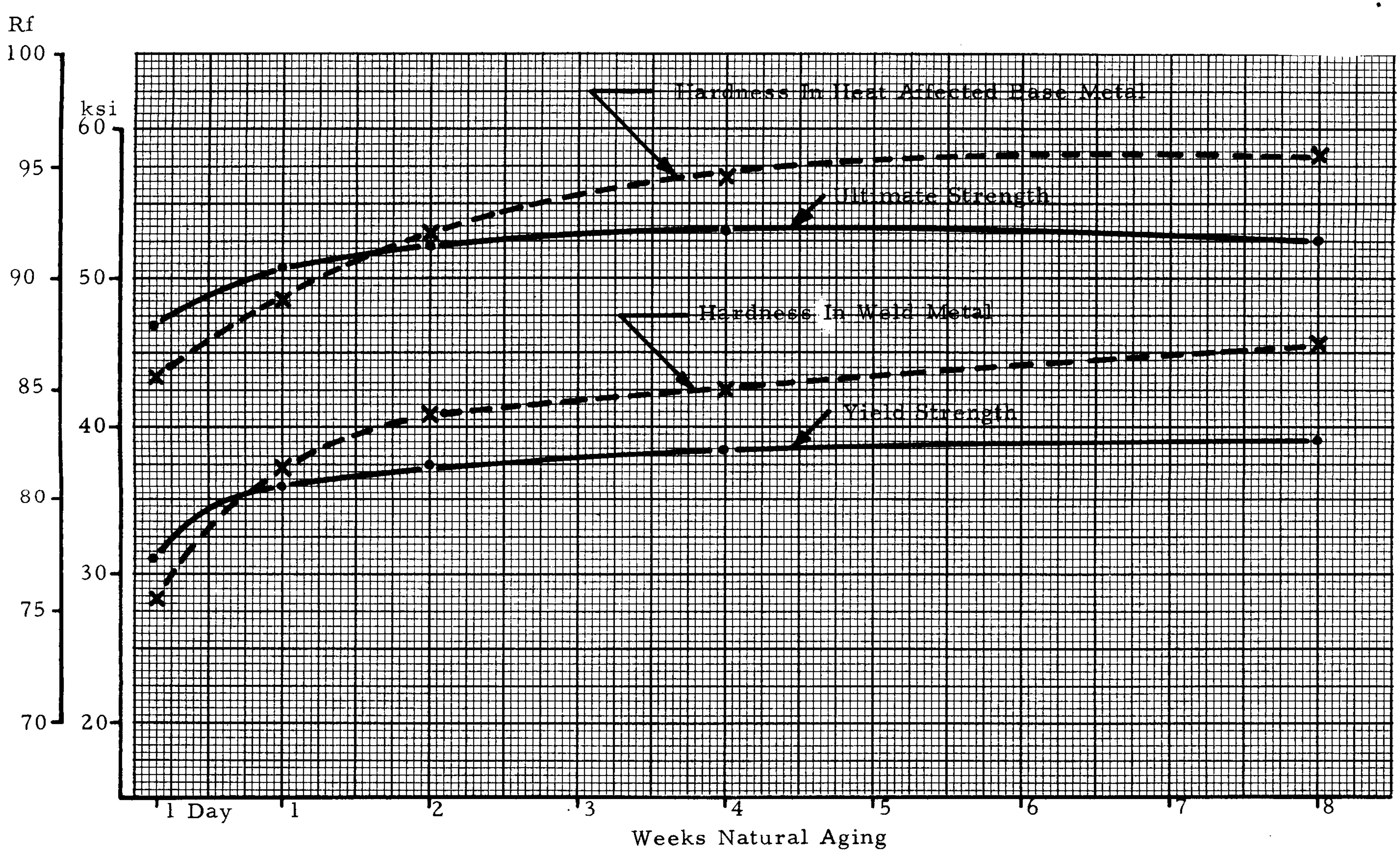


FIGURE 11. RELATIONSHIP BETWEEN HARDNESS,YIELD AND ULTIMATE STRENGTH ON NATURALLY AGING A X7106/X5180 WELDMENT (PANEL B)

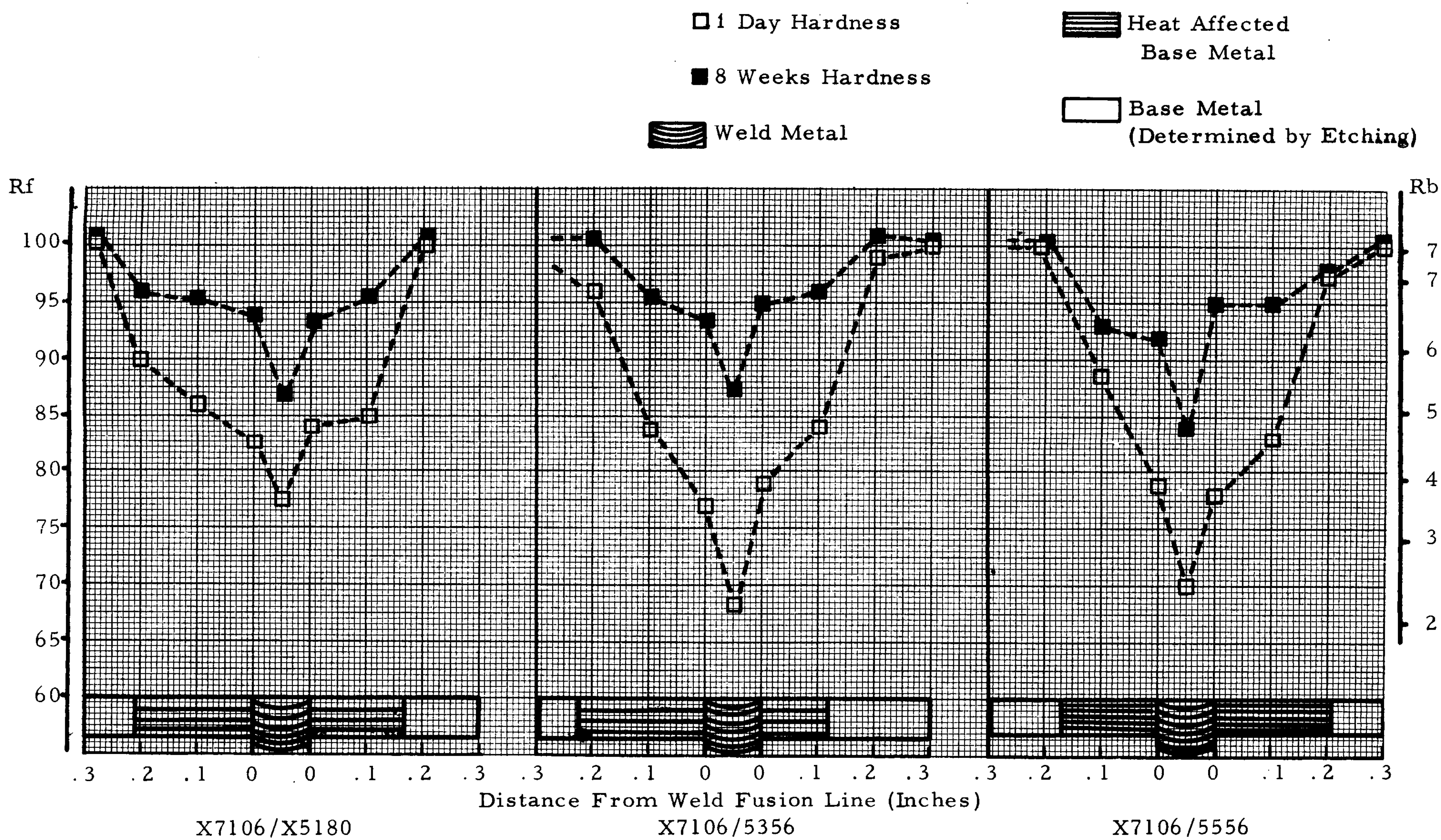
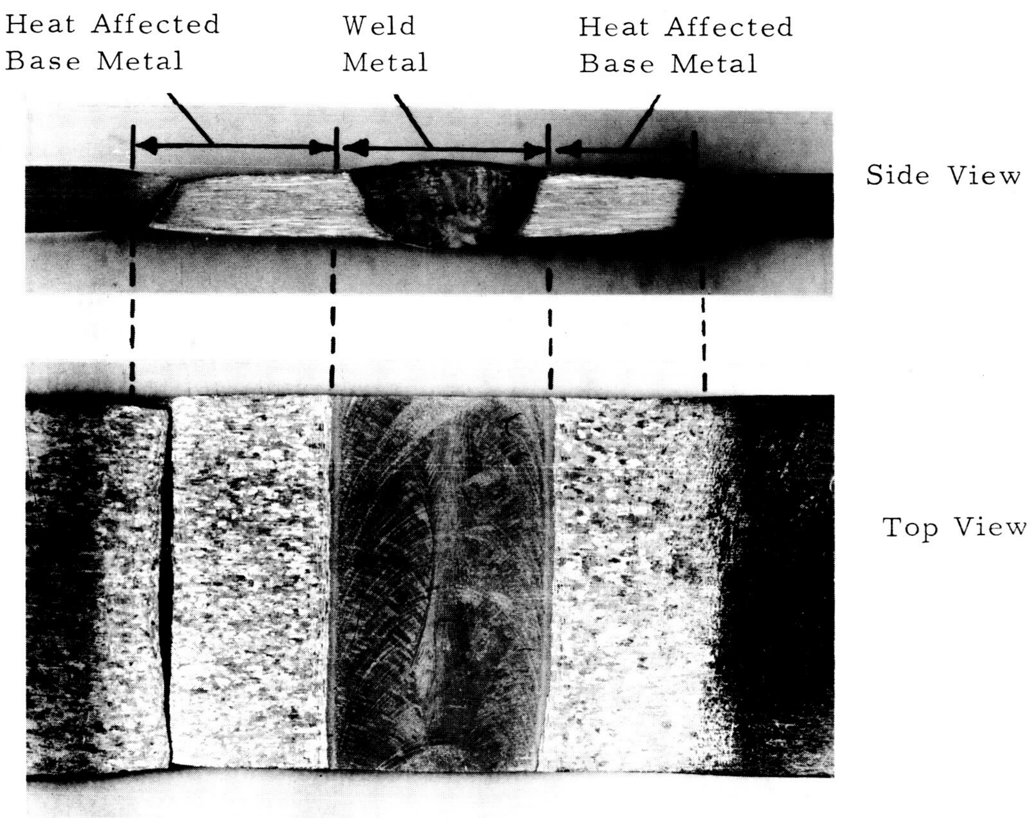


FIGURE 12. INCREASE IN HARDNESS OCCURRING BETWEEN 1 DAY AND 8 WEEKS NATURAL AGING FOR X7106 WELDMENTS, .090 INCH THICK (PANEL B)



Etchant-Keller's 4X

FIGURE 13. TENSILE SPECIMEN THAT FRACTURED IN HEAT AFFECTED BASE METAL OF X7106 WELDMENT

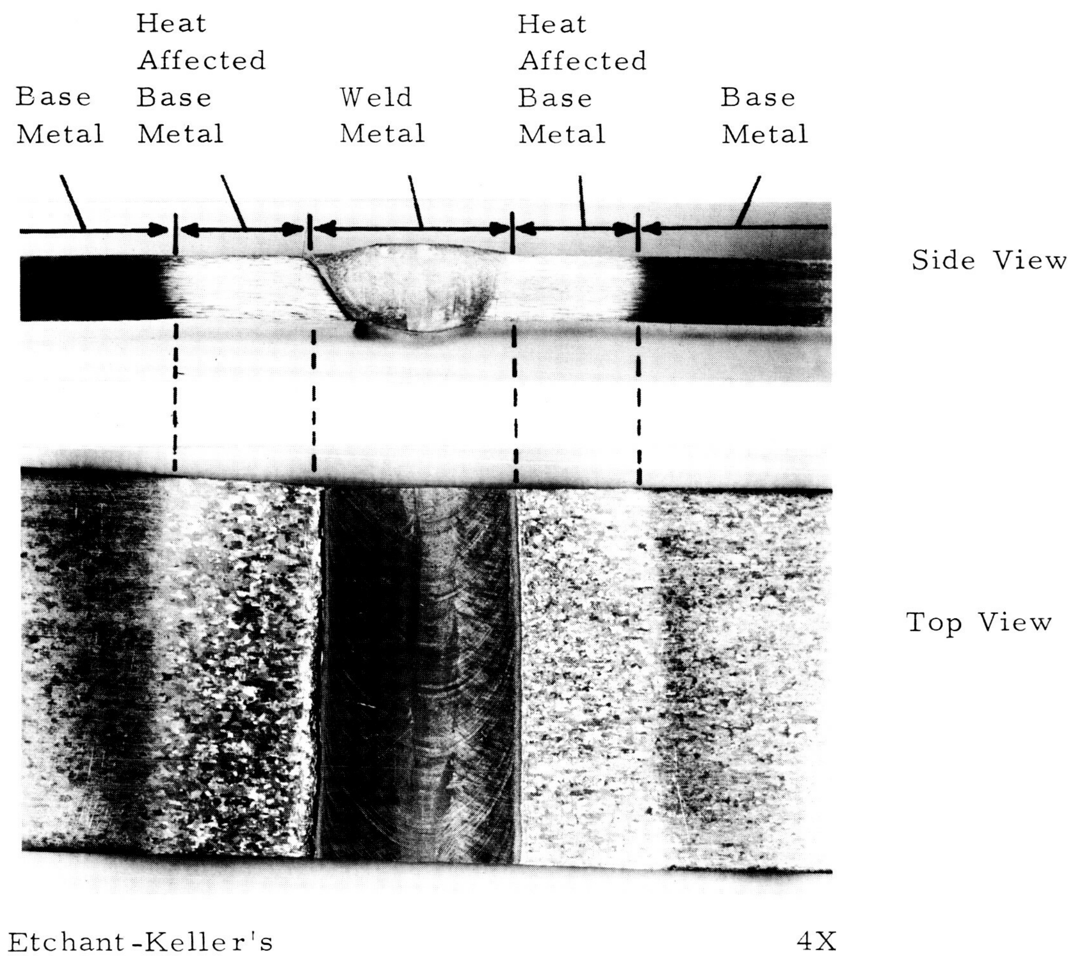
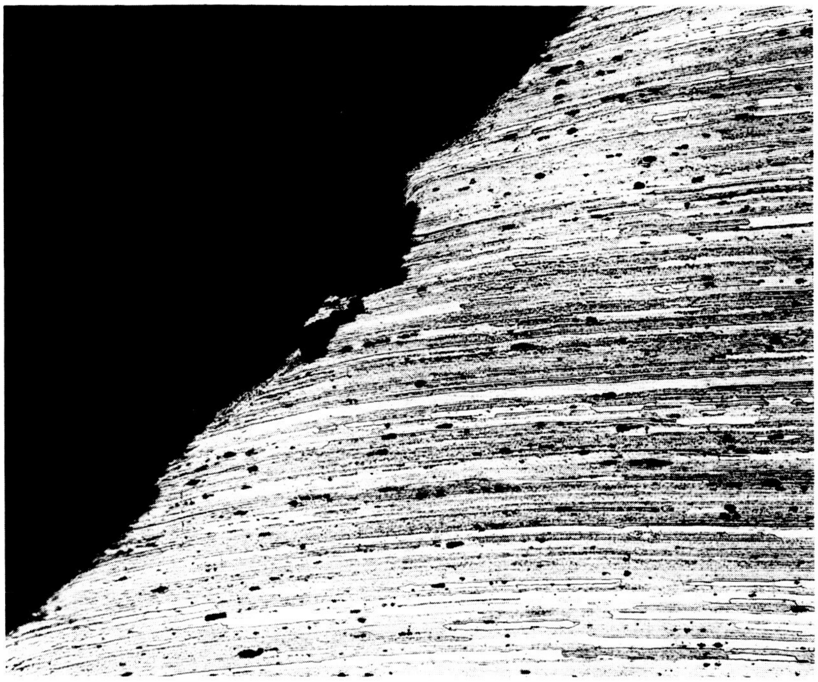


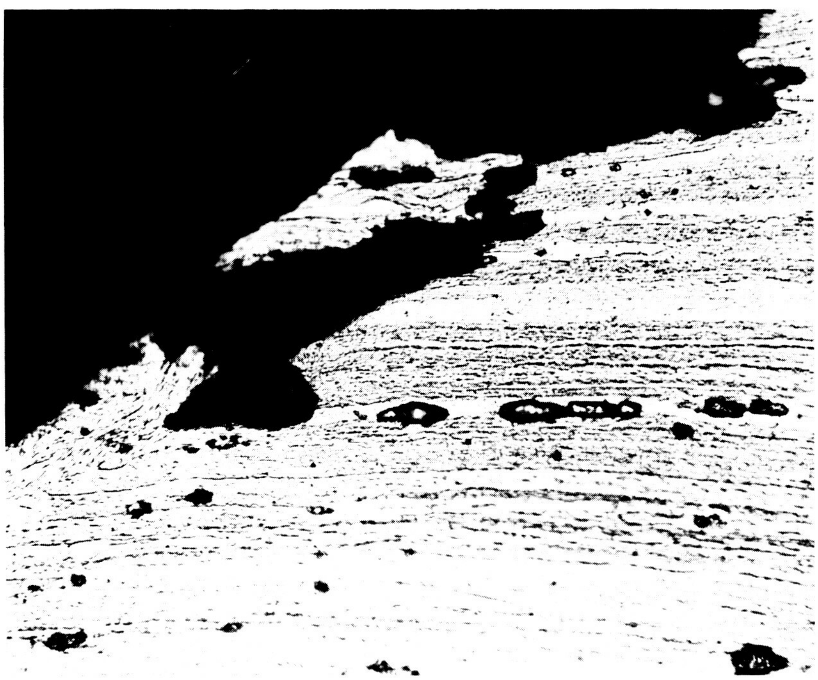
FIGURE 14. TENSILE SPECIMEN WITH FAILURE IN THE WELD FUSION LINE, X7106 WELDMENT

(a)



100X

(b)



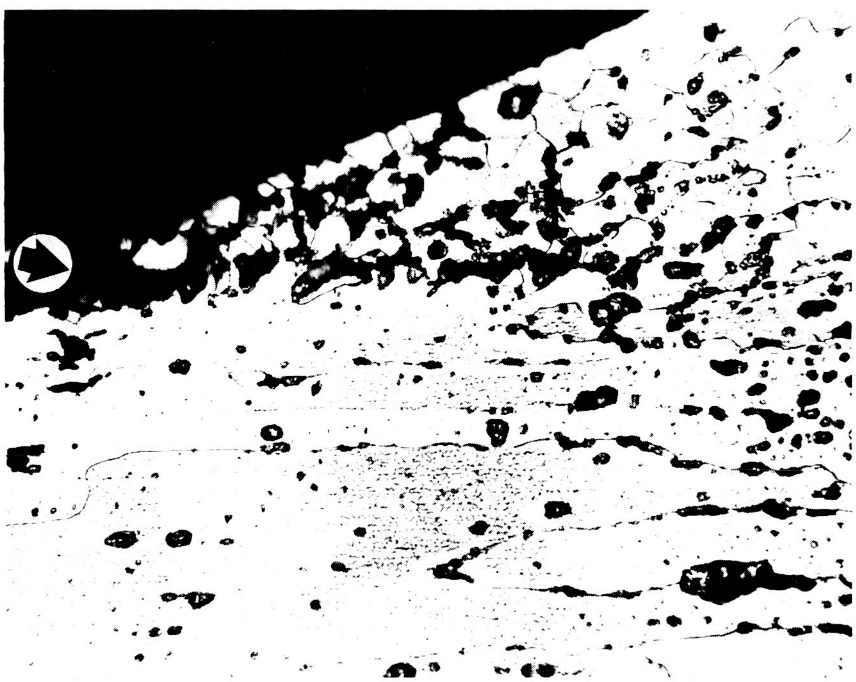
Etchant-Keller's 500X

FIGURE 15. FRACTURED EDGE IN HEAT AFFECTED BASE METAL X7106 WELDMENT

Toe "A"

100X

Toe "B"



Etchant-Keller's 500X

FIGURE 16. TOES OF WELD CROWN OF TENSILE SPECIMEN THAT FAILED IN THE HEAT AFFECTED BASE METAL

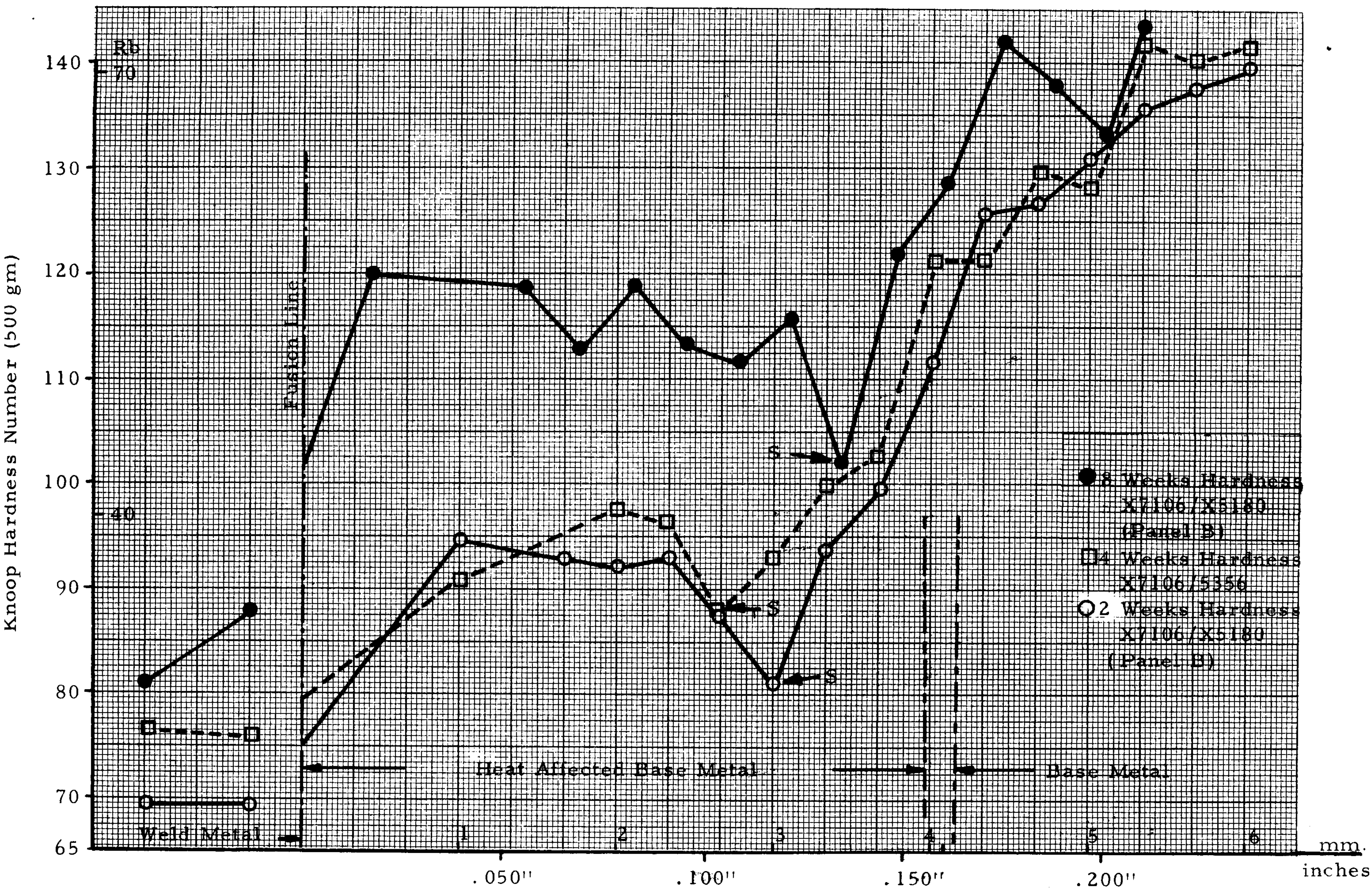
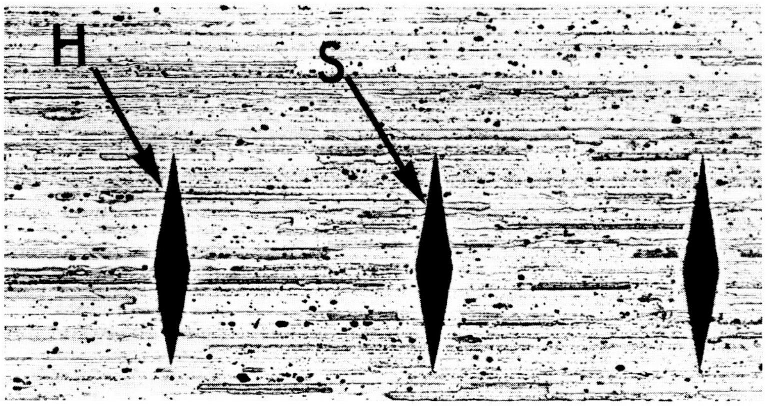


FIGURE 17. MICRO-HARDNESS SURVEY OF X7106 WELDMENTS AFTER VARIOUS NATURAL AGING TIMES

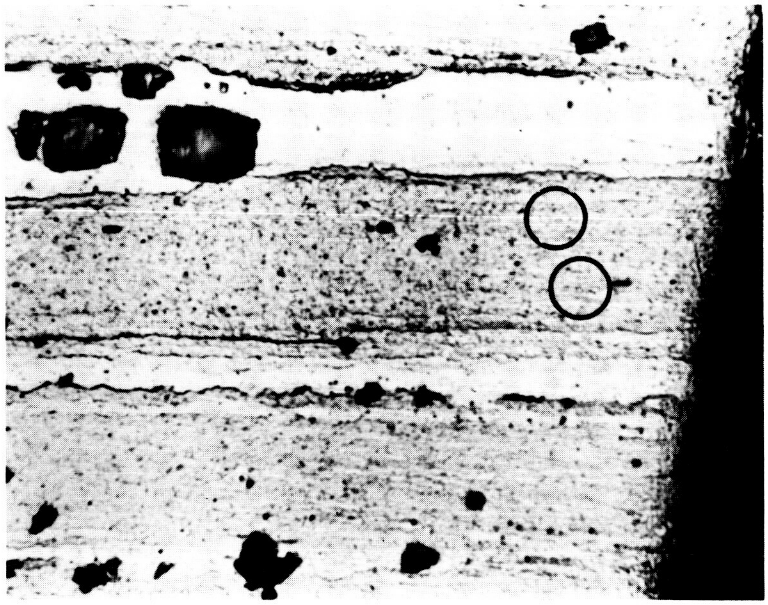
Weld Metal ←



Base Metal →

(a)

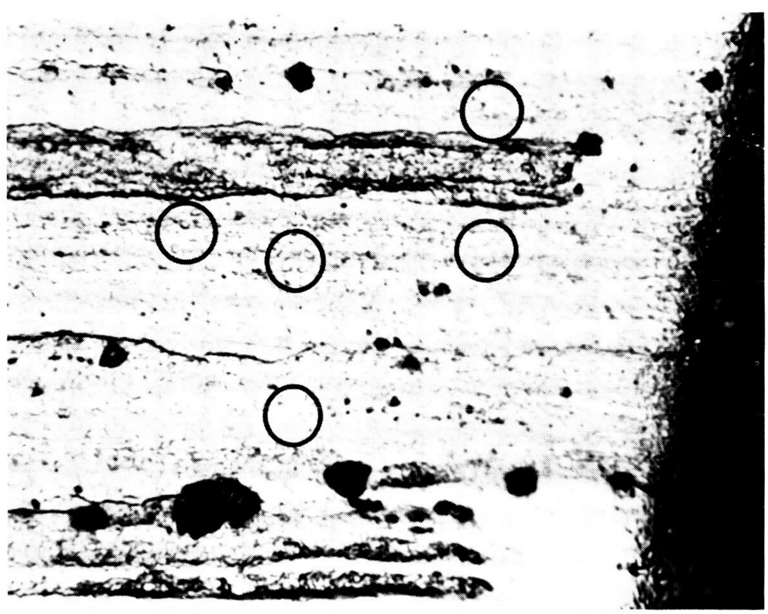
100X



(b)

"H" Indentation

1500X



(c)

"S' Indent ation

Etchant-Keller's

1500X

FIGURE 18. STRUCTURE IN HEAT AFFECTED BASE METAL ASSOCIATED WITH LOW HARDNESS REGION

APPENDICES

APPENDIX A

Study of Applicability of Membrane Stress Equation

To complete the investigation, the applicability of the membrane stress equation to the bulge test was studied. One source of error in the use of the membrane stress equation might be a nonuniform bulge contour, since the radius of curvature enters into the derivation of the equation. The bulge contour of an annealed base metal panel (No. BMA-2) was determined by caliper measurements, while under pressure, at the center and on three chords of 4, 10 and 16 inches (concentric about the center of the panel). The average radius of curvature was computed over each chord. The results were:

Annealed Base Metal 2219 Panel No. BMA-2

Position	Chord (Inches)	Segment Height (Inches)	Average Radius of Curvature (Inches)
2" from center	4	0.14	14.4
5" from center	10	0.49	25.8
8" from center	16	1.13	28.9

The average radius of curvature calculated from the bulge height and die geometry (which is used in the membrane stress equation) was 28.2 inches. This indicates that the panel deviates somewhat from a spherical shape while being pressurized, and that most of the deviation occurs near the center of the panel. A similar set of measurements were carried out on an as-welded panel while under pressure. The results were as follows:

As-Welded 2219 Panel No. BP-60

Position	Chord (Inches)	Segment Height (Inches)	Average Radius of Curvature (Inches)
2" from center	4	.20	10.1
5" from center	8	.32	39.2
8" from center	16	.59	54.5

The average radius of curvature calculated from the bulge height and die geometry was 57.6 inches, agreeing quite well with the average radius of curvature over the 16 inch chord. Comparison of BP-60 and BMA-2 indicates that the more serious discrepancy might occur in welded panels than in base metal panels, since the welded panels fail at much lower values of pressure and deflection.

It is difficult to evaluate the true effect of this nonuniformity on the state of stress in the bulge panel. It apparently has no effect on the membrane stress per se, because the smaller radius of curvature at the panel center would minimize the calculated membrane stress there. Examination of failed panels revealed that in many cases failure initiated at the center of the panel. In the remainder of panels examined, the origin of fracture was not clear. The nonuniformity of bulge contour might be explained by the presence of bending stresses superimposed on the membrane stresses.

Another possible approach is to assume that the membrane stress equation is not applicable to the pressurization of a flat plate. The membrane stress equation was derived for a thin walled vessel with the form of a surface of revolution. Timoshenko* derived a set of equations pertaining to

* Timoshenko, Theory of Plates and Shells, McGraw-Hill, 1930, pp. 333-337.

a thin, flat circular plate clamped at the edge and loaded with a uniform pressure. The equation for the stress at the center of the plate is given by:

$$\sigma = 0.423 \left(\frac{Eq^2a^2}{h^2} \right)^{1/3}$$

where:

σ = stress, psi (circular plate)
E = modulus of elasticity, psi
q = applied uniform pressure, psi
a = radius of circular plate, inches
h = thickness of plate, inches

This equation does not make use of the radius of curvature of the bulged panel and the stress is not uniform over the entire area of the plate. It is maximum at the center and falls to approximately 3/4 of this value at the edge. This stress distribution could result in a nonspherical bulge. The equation is limited to use under conditions of elastic deformation.

The welded panels have all failed at low pressure levels because of the presence of a weld and/or heat affected zone. In most cases, failure occurred with very little, if any, plastic deformation of the base metal. Therefore, it is possible to investigate the state of stress in a welded bulge panel by monitoring strain gages attached to the base metal.

A two element, 90° resistance strain gage rosette was mounted on the 2014-T6 base metal of Bulge Panel 54. It was located approximately one inch from the center of the panel and on the surface which would become convex during the test (outside surface). A number of data points (hydraulic pressure, bulge height, strain readings) were taken before the panel fractured. Membrane stresses were calculated from the pressure and bulge height data; circular plate stresses were calculated from the pressure data; and fiber stresses were calculated from the strain gage data. The stresses calculated by the three methods are summarized in the following table:

Welded (TIG 2014-T6/4043) Panel No. BP-54

Applied Pressure (psi)	Measured Deflection (Inch)	Membrane Stress (psi)	Circular Plate Stress (psi)	Outer Fiber Stress (psi)
10	0.5	5,700	9,150	12,500
64	1.0	17,800	31,500	36,400
82	1.1	20,700	37,300	42,000
102	1.2	23,500	43,300	47,400
123	1.3	26,100	48,900	53,300
147	1.4	28,900	54,900	58,200
171	1.5	31,300	60,900	63,600

The circular plate stress equation appears to produce a better estimate of the stress than does the membrane stress equation. The choice between the two methods should not be made, however, until additional work is initiated to determine the magnitude of bending stresses existing at the point of strain gage attachment.

APPENDIX B

Examination of Hydraulic Bulge Panels and Uniaxial Tensile Specimens

A. Hydraulic Bulge Panels

The hydraulic bulge tests of Panels 17, 18 and 19 exhibited a range of 4.6 ksi for the calculated biaxial ultimate strength. In an effort to explain why this difference occurred an examination was made of the panels. The results of the tests of these panels (originally presented in Table IV of the First Quarterly Report, Contract No. NAS 8-1529, 28 October 1964) were as follows:

Bulge Panel No.	Biaxial Ultimate Strength (ksi)
17	47.0
18	42.9
19	42.4

These panels were prepared by the TIG welding process, using 1/8 inch 2014-T6 base material and 2319 filler metal. The panels were of the "Tee" weld configuration.

The panels were first visually examined and then measurements made of the height and width of the weld crowns and "drop throughs" (penetration crowns). By making these measurements it is possible to estimate to some degree if a variation of current, voltage, travel speed, etc. occurred during welding. Even though records are made at the time the welding is done, some variation in parameters may occur and not be detected.

At most locations along the welds, the crowns and "drop throughs" of the bulged panels were distorted as a result of either clamping the panels in the bulge fixture or straining during bulge testing. The only locations on the welds that could be found in which the crowns and "drop throughs" had not been distorted are depicted in Figure B-1 as "A", "C" and "D". These locations were in the hold down area of the bulge fixture close to the location where the panels begin to deform into a bulge. Ridges machined in the top die of the fixture to prevent slippage of the panels during testing prevented the crowns and "drop throughs" from being distorted at these locations. The measurements of the crowns and "drop throughs" are listed in Table B-I.

Differences in the highest strength panel (No. 17) as compared to the other two were detected and may be summarized as follows:

1) In Panel No. 17 the crown of weld No. 1 at location "B" (Figure B-1) was partially ground off to lay a strain gage.

2) Weld No. 2 of Panel No. 17 had smaller width and height dimensions than the No. 2 welds in Panels 18 and 19 (Note Table B-I). The contour of the "drop through" in weld No. 2 (Panel No. 17) was irregular for a 3-inch length at one end.

Visual examination of the fracture also revealed differences in Panel No. 17. This panel had a relatively straight fracture along the fusion line. Panels 18 and 19 had part of their fractures in the heat affected base metal. At the intersection of the welds the fractures in Panels 18 and 19 shifted from weld No. 2 into weld No. 1. This was not the case in Panel No. 17 where the entire length of the fracture was in fusion line of weld No. 2.

The differences noted in the three panels examined are not considered to be unusual and no indications of abnormal defects were noted in any of the panels. Thus, the observed differences in biaxial ultimate strength must be considered as inherent in bulge tests of these weldments or inherent in the methods presently used in the interpretation of bulge test results.

B. Uniaxial Tensile Specimens

In addition to biaxial ultimate strength variations in the bulge panels, scatter has also occurred in some of the uniaxial ultimate strength results. To obtain the uniaxial strength of a panel, five or six uniaxial tensile specimens are machined from the panel and tested and the results averaged. Large variations in strength have resulted within these groups of specimens in eight of the panels. In the worst case a 12.6 ksi spread between high and low ultimate tensile values existed. To determine the cause of this variation, the tensile specimens from the eight bulge panels have been examined. These bulge panels are listed below:

Bulge Panel No.	Weld Configuration	Welding Process/Base Metal/ Filler Metal
7	Single	TIG/2219-T87/2319
8	Single	TIG/2219-T87/2319
29	Single	MIG/2014-T6/4043
30	Single	MIG/2014-T6/4043
31	Cross	MIG/2014-T6/4043
33	Cross	MIG/2014-T6/4043
35	Tee	MIG/2014-T6/4043
36	Tee	MIG/2014-T6/4043

These data were originally presented in the First Quarterly Report (Contract No. NAS 8-1529, 28 October 1964). This list shows that six of the eight panels were welded by the MIG welding process using 4043 metal and two by the TIG process using 2219-T87 plate and 2319 filler metal.

The fracture faces of each set of tensile specimens were examined for defects that might account for low tensile values. No relationship between the isolated defects observed and low strength specimens was found.

After this examination, the specimens were etched in mixed acid solution to identify the weld deposit in cross section. The resultant weld profile was studied. Measurements of the width and height of the weld crowns and "drop throughs" were made. The location of these measurements are depicted in Figure B-2. Variations of weld profile within each set of specimens were observed. These variations were most pronounced in the MIG specimens. In addition to the weld profile varying from specimen to specimen, differences were noted across the width of some tensile specimens. The weld contours were also found to vary to some extent.

As a result of these variations, it was possible to separate most of the specimens into two general groups; wide weld profile and narrow weld profile. After separation, it was found that the specimens containing the large weld deposits were those having the lowest tensile strength. This was true in both MIG and TIG specimens. Measurements and observation of weld profiles in uniaxial tensile specimens are listed in Table B-II.

Although differences in the width of the weld crowns were noted, the magnitudes of these differences are considered to be comparable to the variations which may be expected in production. In addition, no other defects or abnormal variations were noted. Thus the scatter noted in the uniaxial tensile test results should be regarded as inherent in the particular types of weldments tested.

TABLE B-1

HEIGHT AND WIDTH MEASUREMENTS[1] OF WELD CROWNS AND "DROP THROUGHS" OF BULGE PANELS 17, 18 AND 19

Panel No.	Location		Weld Crown Height (In.)	Weld Crown Width (In.)	"Drop Through" Depth (In.)	"Drop Through" Width (In.)
17	A	Weld #1	.024	.208	.032	.116
	B		.006[2]	----	.026	----
	C	Weld #2	.022	.220	.027	.110
	D		.019	.210	.016	.070
18	A	Weld #1	.019	.220	.026	.112
	B		.020	.215	.032	.120
	C	Weld #2	.025	.240	.025	.125
	D		.022	.247	----	.105
19	A	Weld #1	.020	.230	.007	.120
	B		.019	.235	.030	.121
	C	Weld #2	.029	.235	.027	.120
	D		.025	.240	.027	.105

1 The location of these measurements schematically shown in Figure B-1.

2 Crown partially ground off.

TABLE B-II

RELATIONSHIP BETWEEN WELD PROFILE SIZE AND UNIAXIAL ULTIMATE STRENGTH

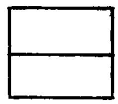
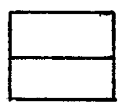
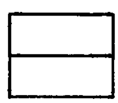
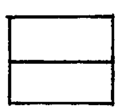
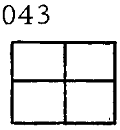
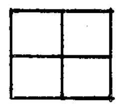
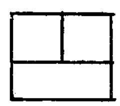
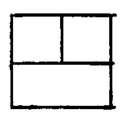
Bulge Panel Number	Panel Identification	Uniaxial Ultimate Strength, (ksi)	Relative Weld Profile Size[1]
7	TIG	41.8	Wide
	2219-T87/	41.9	Wide
	2319	47.8	Narrow
		48.0	Narrow
		47.5	Narrow
		41.2	Wide
8	TIG	42.8	Wide
	2219-T87/	41.3	Wide
	2319	41.6	Wide
		42.1	Wide
		47.8	Narrow
		40.9	Wide
29	MIG	48.9	Narrow
	2014-T6/	36.3	- - -
	4043	45.0	Narrow
		45.5	- - -
		38.1	Wide
30	MIG	46.1	Narrow
	2014-T6/	36.0	Wide
	4043	43.4	Narrow
		43.9	- - -
		39.2	- - -
31	MIG	44.4	- - -
	2014-T6/	40.7	- - -
	4043	34.0	Widest
		46.0	- - -
		45.1	- - -

TABLE B-11 (continued)

RELATIONSHIP BETWEEN WELD PROFILE SIZE AND UNIAXIAL ULTIMATE STRENGTH

Bulge Panel Number	Panel Identification	Uniaxial Ultimate Strength, (ksi)	Relative Weld Profile Size[1]
33	MIG	40.6	- - -
	2014-T6/	40.4	- - -
	4043	45.0	- - -
		38.6	- - -
		47.8	- - -
35	MIG	42.4	Narrow
	2014-T6	31.4	Widest
	4043	35.4	Wide
		40.3	Narrow
36	MIG	44.4	Narrow
	2014-T6/	45.1	Narrow
	4043	43.6	Narrow
		34.9	Wide
		45.5	Narrow

1 Weld profile size of MIG specimens determined by visual observation. Weld profile size of TIG specimens determined by measurements.

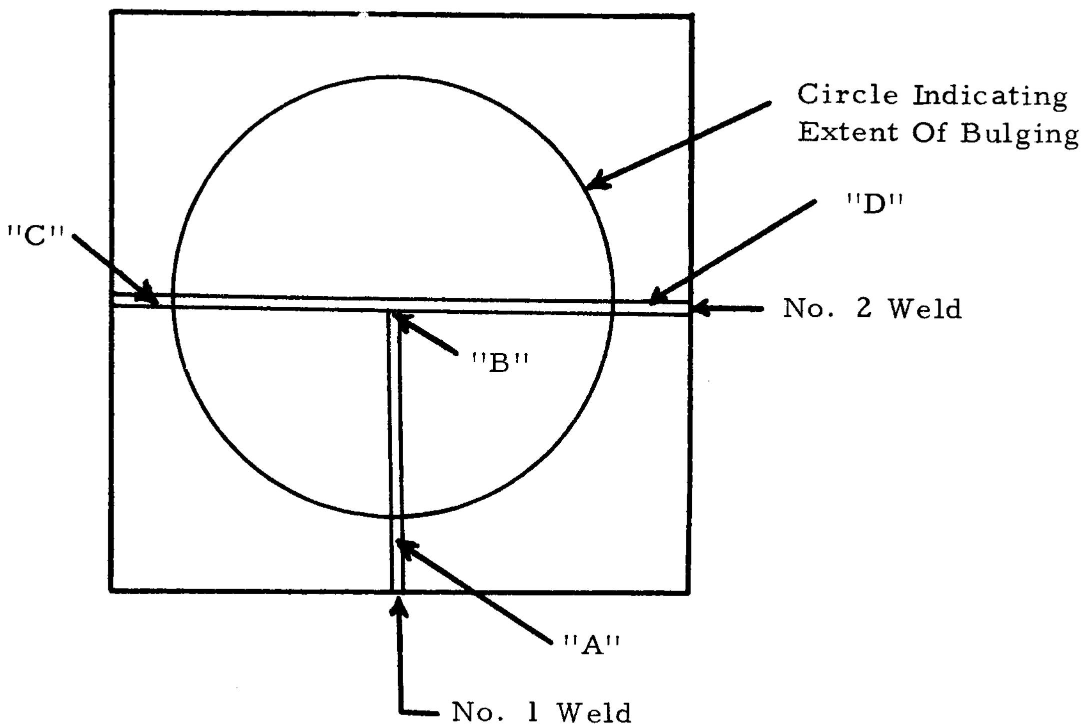
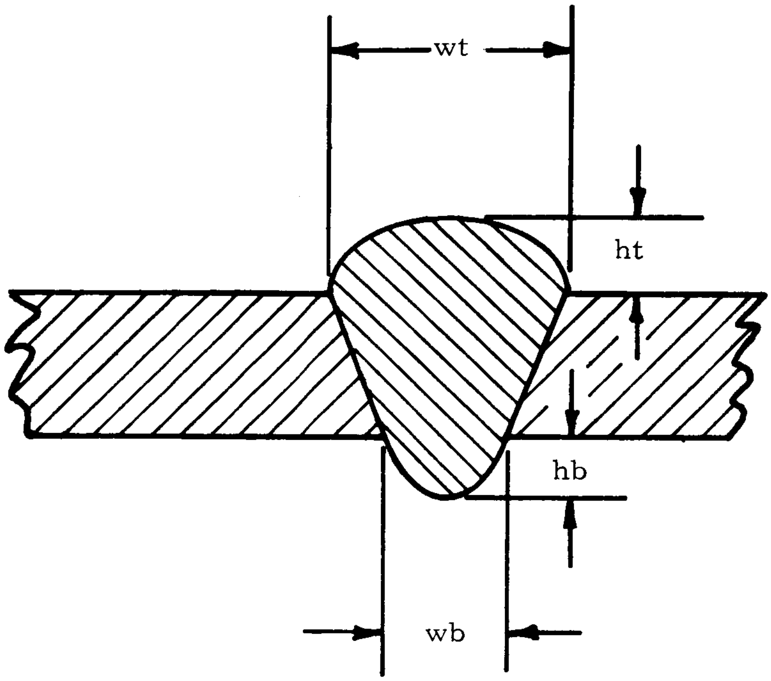


FIGURE B-1. LOCATIONS USED FOR WELD MEASUREMENTS OF BIAXIAL PANELS 17, 18 AND 19



wt = width of crown
ht = height of crown
wb = width of drop through
hb = height of drop through

FIGURE B-2. MEASUREMENTS MADE ON WELD

APPENDIX C

Calculation of Standard Deviation and Lower Tolerance Limit

Symbols:

x_i = ultimate strength (individual test)

$\bar{x} = \frac{\sum x_i}{N}$ = mean ultimate strength

$S_x = \sqrt{\frac{\sum (x_i - x)^2}{N-1}}$ = standard deviation

LTL = $\bar{x}$ - KS_x = Lower Tolerance Limit of ultimate strength

K = Statistical factor computed from non-central T distribution such that 99% of the individual values of ultimate strength will exceed the lower tolerance limit 95% of the time.

N = Number of tests

Sample Calculations: (TIG 2219-T87/2319 weldments)

Uniaxial Ultimate Strength

N = 48, K = 2.88

$\bar{x}$ = 43.5 ksi

$\sum (x_i - x)^2 = 228$

$S_x = \sqrt{\frac{228}{47}} = 2.20$ ksi

LTL = 43.5-(2.88)(2.20)= 37.2 ksi

Biaxial Ultimate Strength

N = 9, K = 4.14

$\bar{x}$ = 35.3 ksi

$\sum (x_i - x)^2 = 78.4$

$S_x = \sqrt{\frac{78.4}{8}} = 3.13$ ksi

LTL = 35.3-4.14(3.13)=22.3 ksi

APPENDIX D

Discussion of Measurement of Residual Stress

The analysis of residual stress in structures has been done for many years and has, in many cases, been found to be a significant factor in the load carrying ability of a structure. Considerable dispute exists over what effect residual stress has on the fracture of ductile materials.

A few comments are in order on the effect of residual stresses in welded panels.

The measurement of residual stresses, especially in welded structures, requires careful attention to detail. Some technique development is also necessary. In the terms of Campus[1] "... measurement of residual stresses requires still more caution than the measurement of ordinary stresses. The measurement of residual stresses often has more the qualitative significance of a proof of the existence of residual stresses rather than the quantitative significance of a precise determination. In other words, it is difficult to evaluate and to verify the degree of approximation; the measurement indicates rather an order of magnitude".

Certainly, the magnitude of the stresses measured in the TIG and MIG welds and areas of heat affected base metal should be interpreted as an order of magnitude measurements rather than as an "absolute" measurement. Due to welding variables no more accuracy than this should be expected. It is, therefore, considered that the data reported (Table VII)

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1 Effects of Residual Stresses on the Behavior of Structures, F. Campus, Residual Stresses in Metals and Metal Construction, W. R. Osgood, editor, Reinhold, 1954, p. 9.

typical results and are within normally expected deviation. Drucker[2] states "Residual stress has been blamed for much of the difficulty in welded structures. Generally, it is not residual stresses on a very small scale which are worried about, but rather stresses which exist over appreciable regions compared with any holes, notches, or other flaws existing in the welds in their neighborhood. A small amount of plastic deformation clearly wipes out residual stresses because they are associated with strains of elastic rather than plastic magnitude. Therefore, residual stresses do not matter in a slightly, or very ductile fracture". Drucker goes on to explain that the "exhaustion of ductility" in tension may be the net result of residual stress, which is to say that in achieving the residual stress, the weld may have had to plastically deform some during cooling, and "used up some ductility", thus there is "less ductility left before fracture". This seems to be the most plausible way of looking at residual stresses in these welded plates, although it is by no means quantitative. It is difficult to measure the amount of strain which occurs during welding; however, this might be an important factor for investigation.

It is, therefore, difficult to assess the importance of residual stress on fracture. This does not, however, appear to be the explanation for the lower biaxial to uniaxial strength ratio as observed in the hydraulic bulge tests.

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[2] "A Continuum Approach to the Fracture of Metals" D. C. Drucker, Fracture of Solids, Drucker and Gillman editors, Interscience, 1962.